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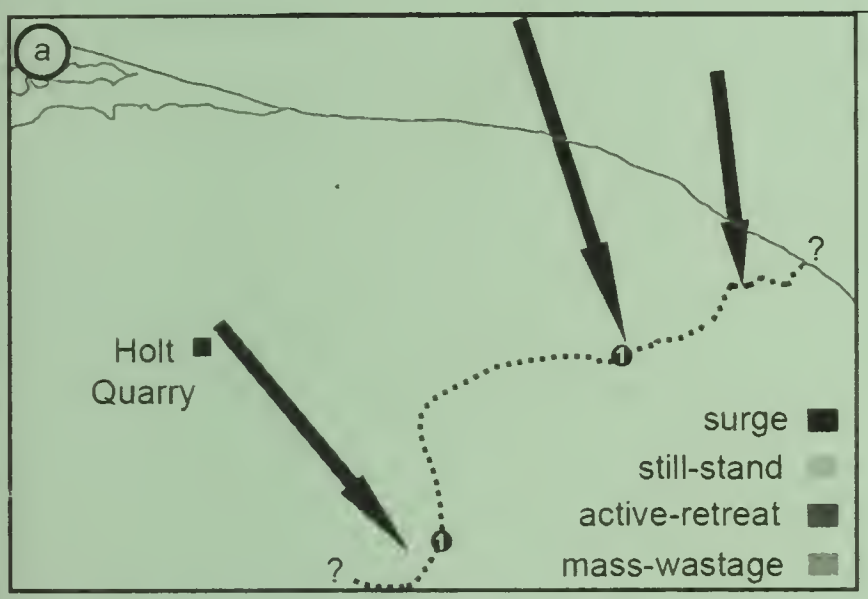
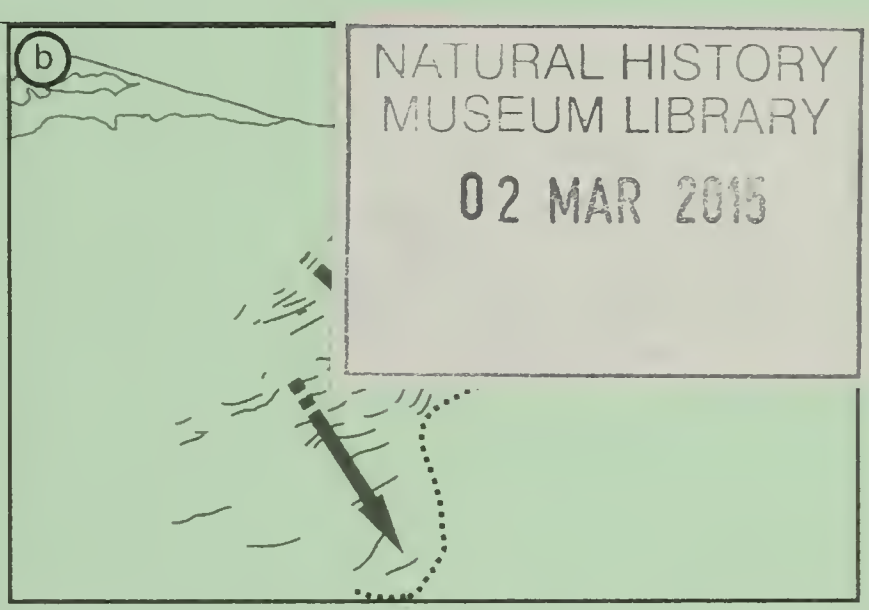
BULLETIN OF THE GEOLOGICAL SOCIETY OF NORFOLK

(FOR ARTICLES ON THE GEOLOGY OF EAST ANGLIA)

NO. 64 2014





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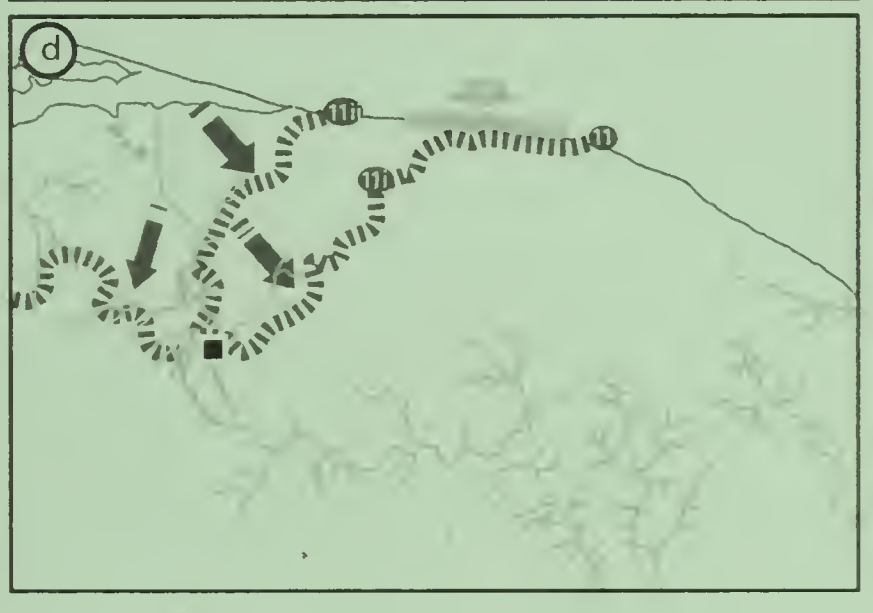

CONTENTS INCLUDE

William Smith's East Anglian Sections

Glacial Outwash Sedimentation, Holt Quarry, Cromer Ridge

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BULLETIN OF THE GEOLOGICAL SOCIETY OF NORFOLK

No. 64 (2014) Published 2015

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EDITORIAL

In this issue of the Bulletin, we extend part of a theme from Bulletin 63, further celebrating the contribution of William Smith to East Anglian geology. As 2015 is the bicentenary of Smith's world famous map, Peter Banham's article is a further timely reminder of the work Smith carried out in East Anglia. Bicentenary celebrations are scheduled across the country and a timetable of events can be found at http://www.geolsoc.org.uk/Events/William-Smith-Bicentenary.

Jon Lee then brings us up to date on recent ideas he has concerning outwash sedimentation and glacial deformation during accretion of the Cromer Ridge. This work is based on field observations at Holt Quarry. Peter Banham notes that William Smith was puzzled by the glacial deposits of East Anglia, and we might speculate that the observations made by Lee would not have been so difficult for Smith to grasp once he understood the context. What a field meeting that would have been!

I am reasonably confident that I will have copy for Bulletin 65 early in 2015 so I hope to keep the publication schedule up to date.

INSTRUCTIONS TO AUTHORS

Contributors should normally submit manuscripts either as word-processor electronic files (MS Word is preferred) or hard copy. When papers are accepted for publication we will request an updated electronic version.

It is important that the style of the paper, in terms of overall format, capitalization, punctuation etc. conforms as strictly as possible to that used in Vol. 53 of the Bulletin. Titles and first order headings should be capitalized, centred and in bold print. Second order headings should be centred, bold and lower case. Text should be 1½ line spaced. All measurements should be given in metric units.

References should be arranged alphabetically in the following style.

BALSON, P.S. & CAMERON, T.T.J. 1985. Quaternary mapping offshore East Anglia. *Modern Geology*, **9**, 221-239.

STEERS, J.A. 1960. Physiography and evolution: the physiography and evolution of Scolt Head Island. In: Steers, J.D. (ed.) *Scolt Head Island* (2nd ed.), 12-66, Heffer, Cambridge.

BLACK, R.M. 1988. *The Elements of Palaeontology*. 2nd Ed., Cambridge University Press, Cambridge. 404pp.

We now make pdf versions of all papers for authors (replacing offprints) and for possible future WWW availability. For this reason we prefer illustrations drawn with a computer graphics package, ideally saved in jpeg format. Thick lines, close stipple or patches of solid black or grey should be used with care as they can spread in printing hard copy. The editor may have diagrams re-drawn professionally and usually the GSN will cover the cost of this. For efficient use of space full use should be made of the width of print on an A4 page when designing diagrams. Half tone photographic plates (if possible reproduced as jpeg files) are acceptable provided the originals exhibit good contrast.

The editors welcome original research papers, notes, comments, discussion, and review articles relevant to the geology of **East Anglia** as a whole, and do not restrict consideration to articles covering Norfolk alone. All papers are independently refereed by at least one reviewer.

OUTWASH SEDIMENTATION AND GLACITECTONIC DEFORMATION DURING ACCRETION OF THE CROMER RIDGE: EVIDENCE FROM HOLT, NORTH NORFOLK, UK

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ABSTRACT

Sections through sand and gravel deposits exposed by aggregate extraction provide further evidence for the development of a complex proglacial / ice-marginal meltwater drainage system during the Anglian Glaciation. Their sedimentology indicates that deposition occurred within a series of anastomosing braided river channels – interpreted as background sedimentation, punctuated by episodes of elevated discharge characterised by unconstrained sheet-flow. Meltwater sediments form part of an extensive (albeit heavily-dissected) sandur that extends southwards from Cromer towards Norwich and developed during a temporary ice-marginal still-stand associated with the formation of the Cromer Ridge 'moraine complex'.

INTRODUCTION

One of the most striking reminders that much of north Norfolk's landscape was shaped by past episodes of glaciation is the Cromer Ridge - a prominent landform that extends westwards from Cromer and Trimingham to Fakenham (Fig. 1) (West, 1957; Straw, 1973; Straw and Clayton, 1979; Boulton *et al.*, 1984; Hart and Boulton, 1991). The Cromer Ridge forms part of a moraine complex produced at the terminus of a Middle Pleistocene ice advance that extended southwards down the current western margins of the Southern North Sea Basin into north Norfolk (Boulton *et al.*, 1984; Hart, 1990; Pawley, 2006; Lee *et al.*, 2013). However, rather than reflecting the maximum ice-marginal position (Hart, 1990; Hart and Boulton, 1991), current interpretations suggest

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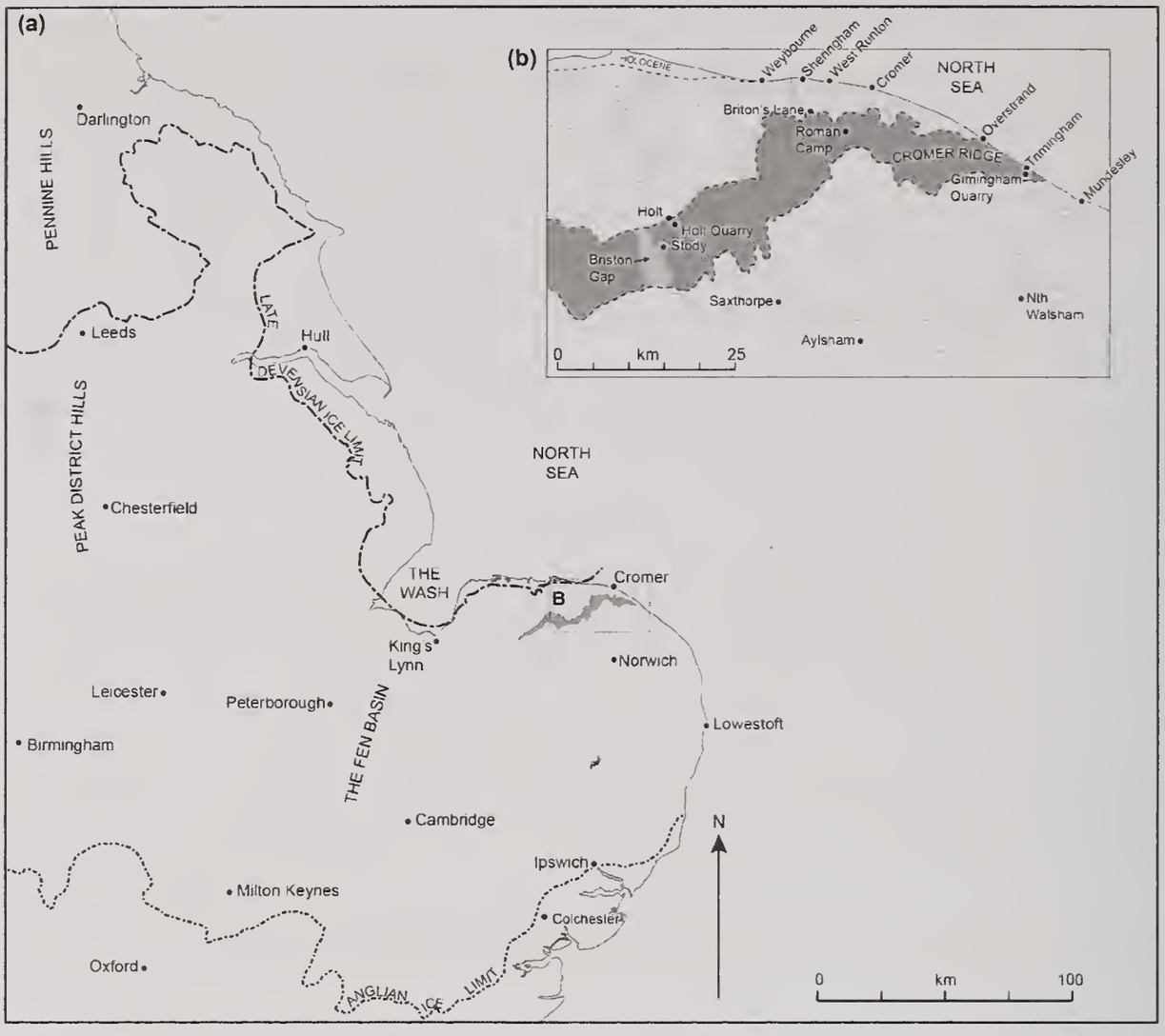

Fig. 1. (a) Map of Eastern England showing the location of the Anglian and Devensian ice limits (Bowen *et al.*, 1986; Clark *et al.*, 2004; Pawley *et al.*, 2006); (b) Inset map of north Norfolk showing the location of sites referred to within the text and the Cromer Ridge.

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that the Cromer Ridge represents a temporary still-stand produced during the retreat of the ice margin from a maximum extent located further to the south (Lee *et al.*, 2013). Boreholes and field exposures through the eastern sector of the Cromer Ridge reveal that the landform possesses a complex internal architecture composed of thrust-stacked slices of pre-existing glacigenic sediment and forms part of the so-called 'Contorted Drift' (Reid, 1882; Boulton *et al.*, 1984; Banham, 1988; Hart, 1990; Ehlers and Gibbard, 1991; Hart and Boulton, 1991; Pawley, 2006; Lee *et al.*, 2013). Draped over the ridge and extending southwards towards Norwich is a heavily-dissected sheet of outwash sands and gravels (West, 1957; Banham, 1977; Straw, 1979; Moorlock *et al.*, 2000;

Pawley *et al.*, 2005; Pawley *et al.*, 2008). The lithology and extent of these gravels is well-established (Solomon, 1932; Straw, 1973; Straw and Clayton, 1979; Moorlock *et al.*, 2002; Lee, 2003; Lee *et al.*, 2004), however, their origin and precise genetic relationship to the Cromer Ridge is generally poorly constrained. Within this paper, the sedimentology of outwash sands and gravels from a site in north Norfolk is examined and placed within the wider framework of ice-marginal retreat.

GEOLOGICAL CONTEXT

The study locality is Holt Quarry (National Grid Reference: TG 073,369) situated approximately 1 km to the south-southwest of Holt, north Norfolk (Fig. 1). Where the original ground surface is preserved, it occurs between approximately 60 to 63 metres OD. This elevated topography forms part of the Cromer Ridge, a pronounced ridge that trends broadly west-southwest to east-northeast across north Norfolk from Thursford in the west, through Holt to Overstrand and Trimingham in the east where the landform intersects the coast (Boulton *et al.*, 1984; Hart, 1990; Lee *et al.*, 2013).

The Cromer Ridge has been widely interpreted as a composite push moraine formed at the maximum extent of a major southwards ice advance into the North Sea Basin (Reid, 1882; Banham, 1988; Hart, 1990; Hart and Boulton, 1991; Lunkka, 1994). The age of the landform has proven controversial (Boulton *et al.*, 1984; Lee *et al.*, 2011a, 2012) with opinions sharply-divided between an Anglian (MIS 12) (Banham *et al.*, 2001; Preece *et al.*, 2009) or later Middle Pleistocene (MIS 6) age (Clark *et al.*, 2004; Hamblin *et al.*, 2005; Rose, 2009). Subsequent OSL dating of gravels that cap the Cromer Ridge demonstrate deposition during the Anglian Glaciation and, by inference, the accretion of the ridge during the same glaciation (Pawley *et al.*, 2008). More recently, Lee *et al.* (2013) has argued that the Cromer Ridge represents the position of a temporary ice-marginal still-stand associated with a more extensive and complex pattern of ice-marginal retreat from a maximum position probably located around Aylsham.

One of the critical themes highlighted by Lee *et al.* (2013) is that a glacier advance does not always result in the deposition of a till unit – often the only record of glaciation may be a range of glacitectonic structures (folds and faults) produced as the ice overrides or pushes into and deforms adjacent substrate (Slater, 1926; Banham, 1977; Evans *et al.*, 2006; Lee and Phillips, 2013). Extensive glacitectonic evidence exists in north Norfolk for several major ice advances that crossed the region and

deposited either no till, or thin till units of very-limited spatial extent (Banham and Ranson, 1965; Banham, 1966, 1975; Lee and Phillips, 2008; Phillips *et al.*, 2008; Waller *et al.*, 2011; Fleming *et al.*, 2013; Lee *et al.*, 2013; Phillips and Lee, 2013). Therefore, the preserved lithostratigraphic record of glaciation in north Norfolk, which has been extensively described by Banham (1968), Lunkka (1994) and Lee *et al.* (2004), provides an incomplete and minimum record of the glacial history of the region (Lee *et al.*, 2008). This was recognised by Banham (1988) who developed a hybrid tectonostratigraphic scheme for the region encompassing both the major lithostratigraphic sub-divisions coupled with major glaciotectonic elements. Subsequent evolution of this scheme encompassing more recent lithostratigraphic and glacitectonic interpretations has recognised six major tectonostratigraphic elements (A1-A6) each associated with a major Middle Pleistocene advance of ice across the region (Table 1) (Lee *et al.*, 2011b, 2013).

Of relevance to this study are the three younger tectonostratigraphic elements (A4-A6). Advance 4 (A4) was produced by a north to south advance of British North Sea ice into north Norfolk. It deposited the Bacton Green Till Member (Third Cromer Till) and associated glaciolacustrine and outwash deposits belonging to the Sheringham Cliffs Formation (Lee *et al.*, 2004). Subsequent retreat of British North Sea ice led to the expansion (A5 – Advance 5) of Pennine ice across East Anglia (West and Donner, 1956; Perrin *et al.*, 1979; Rose, 2009; Scheib *et al.*, 2011). Deformation of the underlying sediment pile as ice advanced across north Norfolk led to the development of a pervasive glacitectonic melange (Hart, 2007; Lee and Phillips, 2008; Phillips *et al.*, 2008; Fleming *et al.*, 2013; Phillips and Lee, 2013) and a highly-localised chalky till (Perrin *et al.*, 1979; Ehlers *et al.*, 1987; Ehlers *et al.*, 1991; Fish *et al.*, 2000; Fish and Whiteman, 2001). A final readvance (Advance 6 – A6) of North Sea ice extended southwards across north Norfolk overriding and tectonising underlying sediments. The ice margin retreated from its maximum extent, producing a series of small 'active-retreat' terminal moraines before reaching a temporary still-stand position whereupon the Cromer Ridge was formed (Lee *et al.*, 2013).

Table 1. Tectonostratigraphic scheme for northern East Anglia showing the primary structural elements relating to the six main Middle Pleistocene ice advances into the region (from Lee *et al.*, 2011b, 2013).

	ICE ADVANCE	GLACITECTONIC SIGNATURE	STRUCTURAL EVIDENCE
A6	Re-advance from N	Large-scale glacitectonism associated with ice-marginal thrust-stacking; Cromer Ridge and smaller ice-contact features.	Listric thrust faults, thrust duplex structures, inverted stratigraphy, large- and small-scale open folding.
A5	Ice advance from W	Large-scale glacitectonism associated with subglacial deforming bed processes (<30m); generation of Bacton Green Till melange; development of terminal moraine – extensional basin complexes; and accretion of 'western facies' *Weybourne Town Till*.	Sheath folding, thrusts, crenulation cleavage, hanging-wall anticlines, over-turned folding, small-scale soft-sediment deformation.
A4	Re-advance from N	Local-scale glacitectonism associated with subglacial deforming bed processes (<4m); accretion of *Bacton Green Till* (subglacial and subaqueous).	Diamicton homogenisation, isoclinal fold noses, small-scale shears, boudinage, tectonic lamination, decollement surfaces, small-scale soft-sediment deformation.
A3	Ice advance from NW	Local-scale glacitectonism associated with subglacial deforming bed processes (<4m); accretion of *Walcott Till*.	Diamicton homogenisation, isoclinal fold noses, small-scale shears, boudinage, tectonic lamination, décollement surfaces.
A2	Re-advance from N	Local-scale glacitectonism associated with subglacial deforming bed processes (<4m); accretion of *Corton Till*.	Diamicton homogenisation, isoclinal fold noses, small-scale shears, soft-sediment deformation.
A1	Ice advance from N	Local-scale glacitectonism associated with subglacial deforming processes (<8m); accretion of *Happisburgh Till*.	Diamicton homogenisation, isoclinal fold noses, small-scale shears, boudinage, tectonic lamination, decollement surfaces.

METHODOLOGY

Exposures at Holt Quarry were examined during several visits to the site between 2002 and 2006. The locations of exposures were recorded using a GPS with elevation datum surveyed relative to a local datum point using standard levelling equipment. Individual exposures were logged with a particular emphasis placed upon describing sediment texture, structure (sedimentary and tectonic) and the nature and geometry of major bounding surfaces. For the purposes of communication, figures displaying the examined exposures show lithofacies codes which summarise the main sedimentary features (Table 2). Palaeocurrent measurements were collected from bedding foresets and plotted (frequency) within rose diagrams. The dip angle and dip azimuth of fault planes were also collected using a compass clinometer, with their relative ordering denoted using standard structural nomenclature (F1, F2, F3....Fn). Fault measurements were plotted within an equal-area lower hemisphere stereographic projection (Schmidt net) as pole to planes, great circles and contours.

Lithological analysis was also undertaken on bulk gravel samples to quantitatively characterise their composition, aid provenance and correlation. Bulk samples were sieved using a combination of wet and dry sieving (Gale and Hoare, 1991) to extract the gravel fraction with counts performed on the 8-16 mm and 16-32 mm to enable comparison with regional data sets (Lee, 2003).

DESCRIPTION AND INTERPRETATION OF EXPOSURES

Three sections from Holt Quarry are described below (Exposures A-C) with Exposures A and B located within a lower excavation-bench and Exposure C within a higher excavation-bench.

Exposure A

Exposure A comprises a 4.5 m thick sequence of sand and gravel capped by artificial ground (Fig. 2). Basal horizons within the section are largely obscured by talus but reveal a 50 cm thick sequence of horizontally-bedded fine to medium sand. Resting conformably upon these sands are a thick (33-52 cm) bed of massive, clast-supported well-sorted cobble-gravel with occasional lenses of coarse sand. Cobbles possess long-axis lengths ranging from 6-14 cm with flint clasts typically well-rounded and spherical (i.e. 'cannon-shot'). They are overlain conformably by a 30 cm thick unit of massive to horizontally-bedded sand, truncated in-turn, by a series of shallow (up to 0.45 m depth)

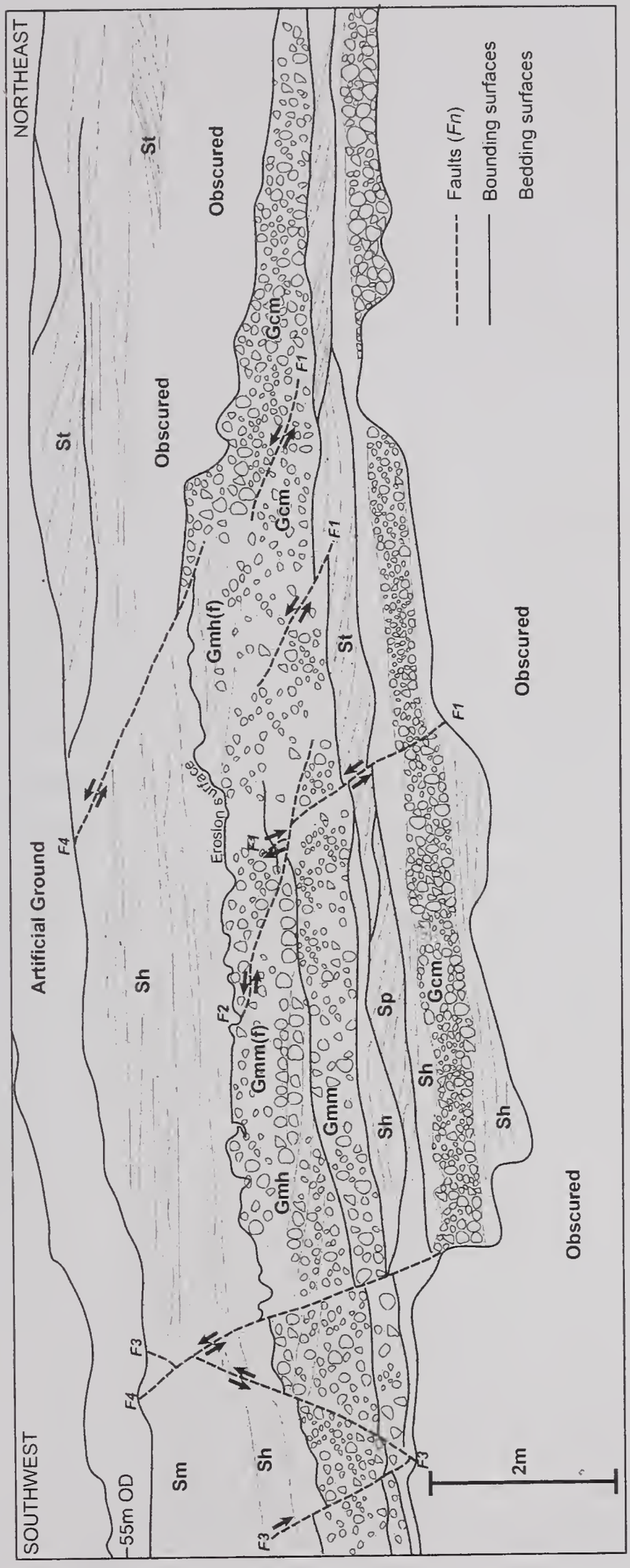

Fig. 2. Diagram of Exposure A showing the sedimentology of the sands and gravels. Bold letters refer to lithofacies codes (see Table 2).

Table 2. Lithofacies coding for nomenclature used within exposure diagrams.

G	**Gravel**
S	**Sand**
F	**Fines (silt and clay)**
-m-	Matrix-supported
-c-	Clast-supported
--h	Horizontally-bedded
--p	Planar cross-bedded
--t	Trough cross-bedded
--m	Massive
--l	Finely laminated
--r	Ripples
---(c)	Convolute bedding

cross-cutting sand-filled channels. Channels exhibit slightly irregular bases and contain horizontal-bedded, planar- and trough cross-bedded sets of fine to medium sand with foresets dipping towards the south and south-southwest (Fig. 3a) Resting conformably upon the channel sediments are a 1.2 to 1.4 m thick unit of matrix- to clast-supported cobbles and gravel. Overall, the unit fines-upwards into medium-coarse sandy gravel and is gently-inclined towards the southwest. Gravels are largely massive in structure with faint bedding discernible by sharp changes in clast size and sorting. Gravels are truncated by early phase (F1) faulting that comprises three moderately to steeply-inclined reverse faults. Throws of between 15 and 25 cm were recorded with fault planes dipping northwards (Fig. 4). A second stage (F2) of low-angle thrust faulting truncates F1 faults with the fault plane also dipping northwards.

F2 faulting is truncated in-turn by sands that cap the sequence. The shape of the contact between the gravels and overlying sand unit (up to 2.3 m thick) varies along the length of the exposure. At the northeast end, sands occupy a deep (1.3 m) irregular-shaped channel incised into the underlying gravels, whereas to the southwest, the contact exhibits smaller-scale irregularity comprising localised small scours, flame-like contortions and disharmonic inter-folding. Bedding within the main sand- body comprises sets of horizontally- and trough-cross bedded sand, which are dissected to the northeast by a broad, shallow channel infilled by trough cross-bedded sand. Two subsequent episodes of faulting deform sediment within the upper parts of the exposure.

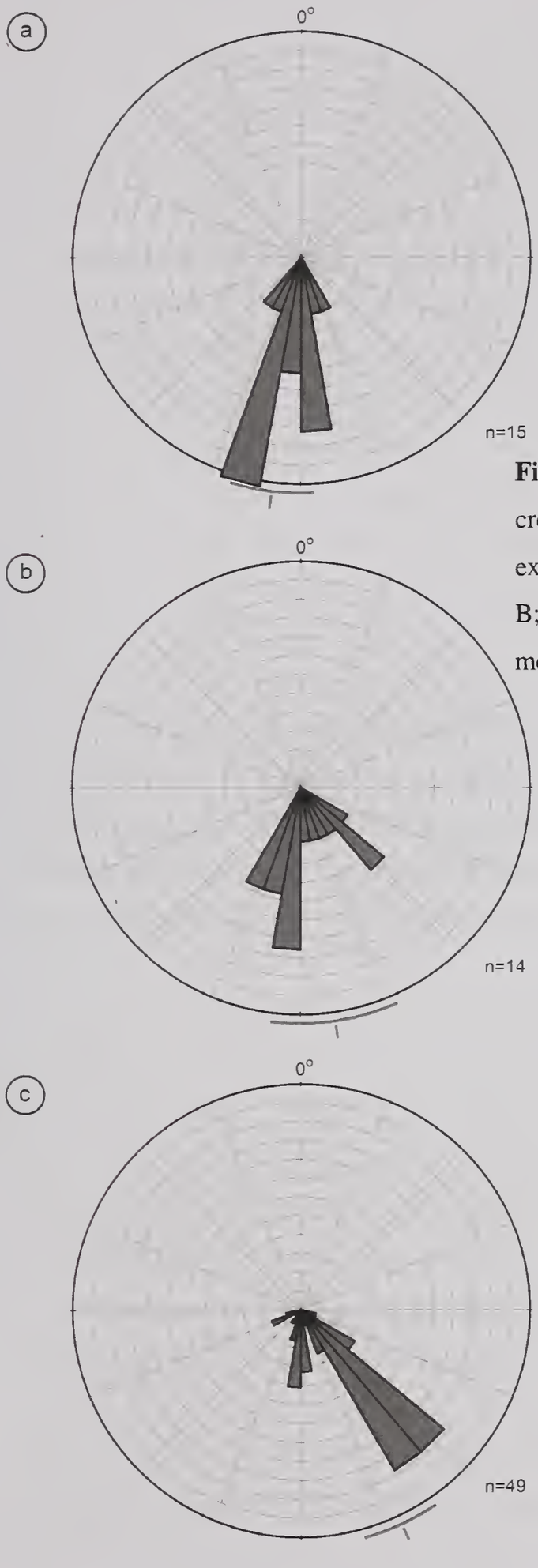

Fig. 3. Palaeocurrent measurements from cross-bedding foresets taken throughout exposures: (a) Exposure A; (b) Exposure B; (c) Exposure C. Grey ticks equate to mean flow directions.

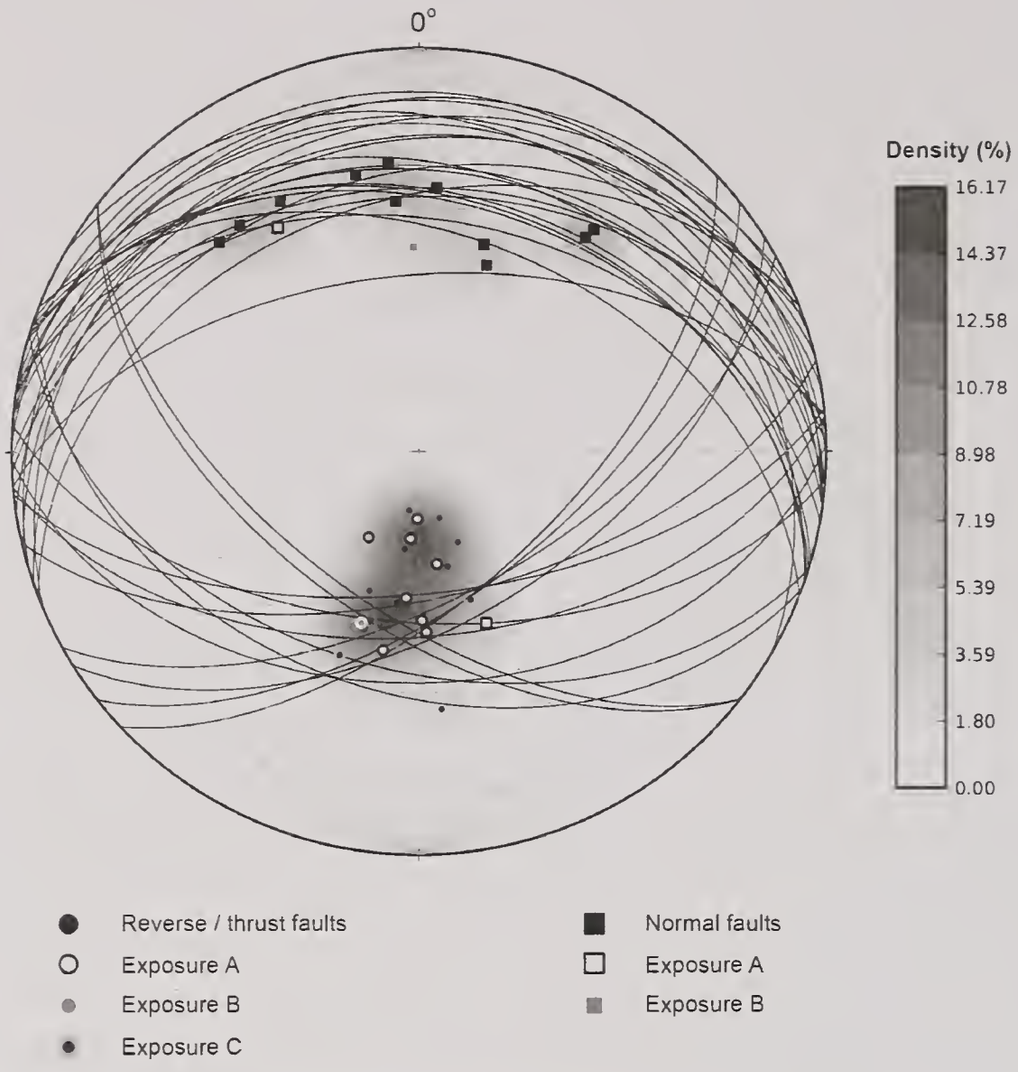

Fig. 4. Lower hemisphere stereographic projection (Schmidt) of normal and reverse / thrust faults measurements showing poles to planes, great circles and contours. Data points (poles to planes) are attributed Exposures A-C or to small un-described section (infilled black circles and squares).

F3 faulting comprises two steeply-dipping normal faults situated at the southwestern end of the exposure that form a down-faulted graben structure - the amount of throw is 25 cm. Cross-cutting F3 are two further F4 faults (Fig. 4). The first fault, located at the southwest end of the exposure, is a steeply-inclined reverse fault that dissects the entire observable sequence. The footwall-block within this fault has been downthrown towards the north by approximately 5 cm. The second fault dissects the higher sands and uppermost gravelly sands and is a moderately-inclined reverse fault that dips towards the north-northwest.

Sand and gravel units within Exposure A detail subaqueous sedimentation driven by variations in flow regime and sediment supply. The lowermost horizontally-

bedded fine sand records lower plane bed flow and subaqueous bar-top deposition (Miall, 1978). The overlying unit of well-sorted cobbles are interpreted as the product of bedload deposition from high-energy tractive sheet-flow with winnowing of the sand fraction. Subtle and highly-localised drops in flow regime enabled the deposition of occasional lens-shaped sand bodies. Overlying horizontally-bedded sands indicate a return to a lower plane bed flow regime and the deposition of fine to medium grained sand. Dissection of these sands by several cross-cutting channel structures record channelised flow associated with several small and laterally-migrating channels. Sedimentation within these channels was driven by the down-current migration of straight-crested (planar cross-bedding) and lunate (trough cross-bedding) sandy bedforms. The overlying unit of massive to faintly-bedded gravels with variable sorting suggest a switch-back to sedimentation of coarse clastic bedload from tractive sheet-flow characterised by frequent but subtle changes in flow regime and sediment supply. An overall fining-upwards in particle size is interpreted as evidence for reducing flow conditions. Sands and gravels are separated from the overlying sand unit by an erosion surface that includes the channel-structure at the northwest end of the exposure. This surface was probably generated by a high-energy tractive current that variably scoured and down-cut into the underlying unit. Sedimentation continued with the deposition of the horizontally-bedded sands under upper flow regime conditions, and the localised incision of small channels. Flame-like contacts and disharmonic inter-folding of the two units are indicative of rapid deposition and loading of a seemingly water-saturated sand and gravel.

Normal faulting and the graben structure (F3) are likely to be the product of consolidation induced by either drying of the sediment pile or loading. By contrasting, the three phases of reverse faulting (F1, F2 and F4) indicate the application of later shear-stresses to the sediment pile. Their geometric relationship to sediments within the exposure demonstrate that they were generated during (F1 and F2) and following deposition (F4).

Exposure B

Exposure B is situated approximately 100 m to the southwest of Exposure A with sediments partly-obscured by talus (Fig. 5). Basal horizons comprise thin (10-15 cm thickness) sets of horizontal-laminated and planar cross-bedded fine-medium sand, with foresets dipping towards the southeast (Fig. 3b), passing northeast-wards into rippled

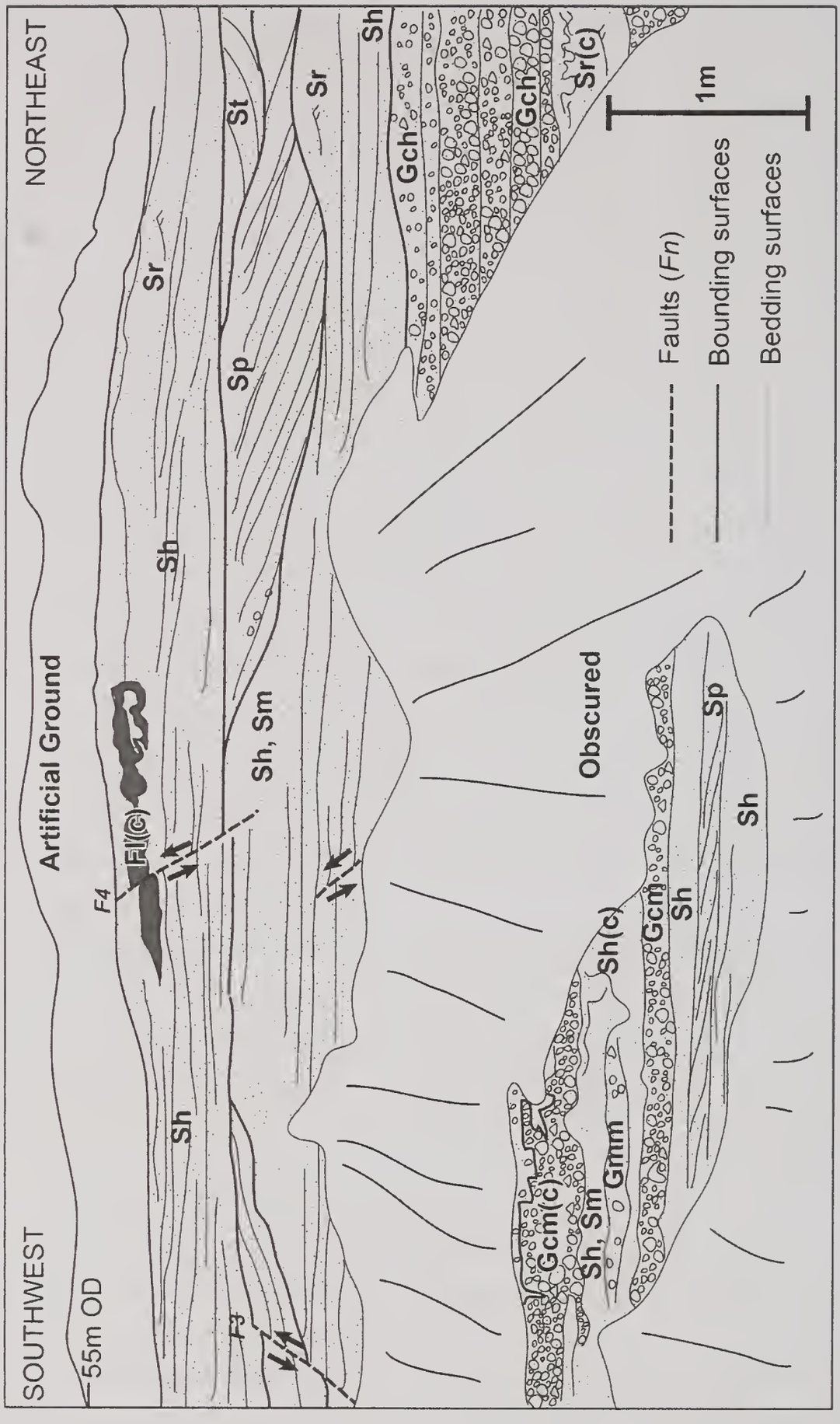

Fig. 5. Diagram of Exposure B displaying the sedimentology and geometry of the sand and gravel deposits. Bold letters refer to lithofacies codes (see Table 2).

(Type-B) and horizontally-laminated sand. Occasional thin horizons of fine sand / silt exhibit small convolute bedding structures. Basal sand horizons are overlain conformably by a 1 m thick unit of bedded gravel and sand. Gravel beds are variably clast- to matrix-supported, exhibiting weakly-developed horizontal stratification defined by subtle vertical changes in clast size and sorting. In the southwestern half of the section, gravels are separated by a thin (30 cm thickness) bed of massive to horizontally-laminated fine sand and a small gravels lens with sand laminae often exhibiting convolute bedding. The base of this gravel unit is vertically offset between the southwest and northeast parts of the section by approximately 35 cm. The conformable nature of the contact with underlying sandy units indicates, tentatively, that bedding could be offset by faulting.

The remaining 1.5 m of the section is composed predominantly of sand. Horizontally-laminated, rippled (Type-A) and massive fine to medium sands drape the underlying beds of gravel. They are dissected at each end of the section by broad, shallow (up to 40 cm) channel structures with gently undulating bases. Channels are infilled by sets of planar and trough cross-bedded sand with foresets dipping in a southeast to southwards direction (Fig. 3b). Both channels are truncated in-turn by a 0.5 m thick unit of horizontally-bedded, massive and rippled sand which forms the uppermost unit within the section. Extensional (normal) faulting deforms the lower horizons of this sand unit and the underlying left-hand channel margins. Faulting is steeply-inclined with the footwall block downthrown towards the south (Fig. 4). A lens of finely-laminated silt and clay crops-out within the centre of the section. The lower contact of the lens possesses diffuse to flame-like margins. The lens is offset by a moderately-inclined reverse fault that dips northeastwards with a throw of 8 cm (Fig. 4). Deformation can be traced down-profile approximately 60 cm with the fault truncated up-profile by artificial ground.

Sediments within Exposure B record subaqueous sedimentation associated with a variable flow regime. The basal horizontally-laminated fine-medium sand reflects deposition under lower plane bed conditions associated with subaqueous sediment transport over a bar-surface. Planar cross-bedding records the down-current migration of small straight-crested subaqueous bedforms. Type-B climbing ripples are produced by forward and vertical accretion of small ripples under a constant flow regime and sediment supply. Together with the convolute bedding structures, they suggest that sedimentation was rapid with localised sediment loading and dewatering. Overlying

gravel beds record sedimentation from higher-energy bedload currents transporting gravel-sized particles by rolling and/or saltation. Changes in particle size and sorting between beds reflect minor changes in energy regime with the lateral (southwest) switch to sand-dominated deposition interpreted as lower flow conditions within a more marginal locality. Horizontally-bedded and massive sand units that cap the section reflect a switch to deposition under lower plane bed conditions probably associated with sediment-laden currents flowing over a bar-surface. Subtle drops in flow regime and sediment supply are demonstrated by the generation of small non-climbing ripples. Meanwhile, the development of shallow channel structures indicate temporary phases of incision, channelled-flow, and the progradation of straight-crested (planar cross-bedding) and lunate (trough cross-bedding) bedforms. At the top of the section, the silt and clay lens records a dramatic drop in flow regime to gently-agitated to still-water conditions. The lensoid geometry suggests that sedimentation probably occurred within a gentle undulation in the bed surface.

Exposure C

Exposure C is located within a temporary higher-level bench approximately 2 m higher than the top of Exposures A and B (Fig. 6). The exposure is dominated by sand-rich units which, based upon their elevation and sedimentology, appear to comprise a vertical continuation of sediments described within previous exposures.

The base of the sequence within Exposure C comprises sets of planar cross-bedded fine to medium sand which total 2.2 m thickness with foresets dipping towards the southwest (Fig. 3c). Within the lower horizons of the unit, a thin (15 cm) lens of massive silt drapes an underlying foreset. Cross-bedding and the silt lens is truncated by a major bounding surface which is overlain by further planar cross-bedding. Palaeocurrent measurements show that foresets dip towards the south and southwest. Cross-bedded sands are truncated in-turn by a bounding surface that dips towards the southeast with overlying bedding comprising horizontally-laminated sands, passing upwards into massive and rippled (non-climbing) fine sands. Sands are unconformably overlain by stratified gravels and sands that progressively infill a scoured surface and form a wedge-shaped bed that thickens (20 cm to 50 cm) eastwards. The infill of the scoured surface comprise massive sand, passing upwards into trough cross-bedded sets of gravel and sand, horizontally-laminated sand, and finally, planar-cross-bedded gravel with foresets dipping variably towards the southwest, south and southeast (Fig. 3c).

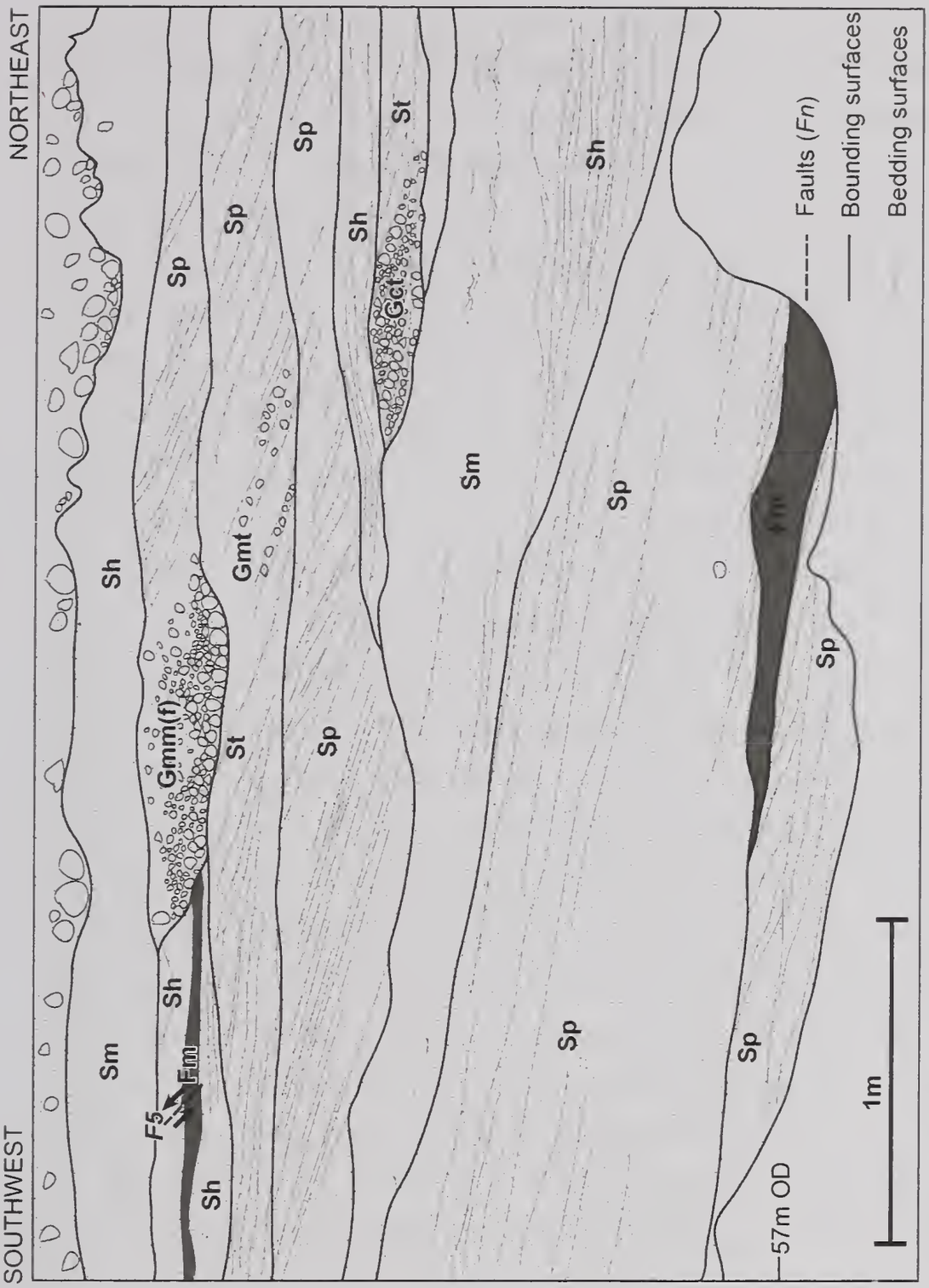

Fig. 6. Diagram of Exposure C displaying the sedimentology and geometry of the sand and gravel deposits. Bold letters refer to lithofacies codes (see Table 2).

They are overlain by planar- and trough cross-bedded sands and sandy gravels that rest upon a gently undulating lower bounding (erosional) surface. Sands pass vertically into horizontally-laminated sands that grade upwards into massive clayey silts, and in-turn, horizontally-laminated sand. Bedding is locally offset by a small steeply-inclined reverse fault (F5) that dips toward the northeast with a throw of about 1cm (Fig. 4). Laterally these sands and silts are cross-cut by a broad and shallow channel structure containing a 30 cm thick unit of massive, matrix-supported gravel that fines-upwards

and grades laterally into planar-cross-bedded sand. The top of the sequence is marked by a 20 cm thick unit of massive to horizontally-bed sand rests upon a sub-horizontal and slightly undulating lower erosion surface.

Deposits observed within Exposure C record phases of a rapidly-aggrading sediment sequence, interrupted by lateral sediment reworking associated with the migration of large subaqueous bedforms (dunes). Planar cross-bedded sands that crop-out at the base of the exposure characterise the down-current migration of straight-crested dunes. Sand-dominated sedimentation was punctuated by bedform stabilisation and suspension-settling of fine sediment under low-energy conditions. Reactivation of higher flow conditions, lateral sediment reworking and sandy bedform migration, is indicated by cross-cutting bounding surfaces and overlying cross-bedding. Bedding is progressively buried by horizontally-laminated, massive and rippled sands implying rapid deposition under lower plane bed conditions, culminating with a drop of energy regime and sediment supply (rippled sand). The overlying angular erosion surface records a phase of scouring with partial-infilling of the bed topography by migrating sand and gravel (lunate dunes) bedforms. Subsequent burial of this surface and the accreted sediments was driven by the reactivation of bedform migration indicated by sets of planar- and trough cross-bedded sands and gravelly sand. Plane-bed flow over bar-surfaces in suggested by overlying horizontally-laminated fine grained sands with a temporary drop in flow-regime enabling the massive to faintly-laminated clayey silts to be deposited. Deformation of bedding by a small reverse fault (F5) was produced by the lateral application of compressive stress to the sediments. Truncation and erosion of these deposits followed, with sedimentation of the massive gravels that grade upwards and laterally into gravelly sands and planar-cross-bedded sands. Collectively they indicate the transition from deposition of coarse bed-load deposition to the down-current migration of straight-crested sandy bedforms associated with a slight reduction in flow regime. At the top of the observed section, the massive and horizontally-laminated sands record a final switch to lower plane bed conditions and deposition upon the surfaces of subaqueous bedforms.

COMPOSITION OF GRAVEL LITHOLOGIES

Seven bulk samples were analysed to determine the clast lithological composition of gravel units (Table 3). Samples consist of high quantities of flint in both the 8-16 mm (84.6-96.3%) and 16-32 mm (91.1-100.0%) fractions. Chatter-marked species become increasing prominent within the coarser size range and black flint (11.6-32.1%) is common within the 8-16 mm fractions. Quartzose lithologies form a common component of the 8-16 mm fraction representing between 3.3-8.2% of the total clast assemblage. Jurassic clasts, and Carboniferous cherts are present within most samples, whilst far-travelled exotics – including schistose lithologies, red sandstone, granite and porphyry, typically form less than 1% of the clast population.

DISCUSSION

Palaeoenvironmental Reconstruction

Exposures at Holt Quarry display packages of stratified sand and gravel that identify phases of unconstrained sheet-flow during high peak discharges, and lateral channel and bedform migration under lower flow conditions.

The base of the sequence within Exposures A and B comprises horizontally-laminated and planar cross-bedded sands. These sands record upper flow regime conditions developed on top of subaqueous bar-surfaces with a temporary drop in flow regime enabling small straight-crested dunes to form and migrate down-current. Angular and cross-cutting bounding surfaces, channel structures and associated channel-fills are interpreted as the product of lateral erosion and anastomosing channel migration upon a fluvial braid plain (Rust, 1972; Miall, 1977).

They are overlain (Exposures A and B) by massive to faintly-stratified, clast- to matrix-supported gravels deposited from bedload transportation (i.e. rolling / saltation) under high-energy flow conditions with, in-places, a winnowing of the sand fraction (clast-supported). Vertical and horizontal changes in sorting and clast size record subtle variations in flow regime and sediment supply. Gravel units typically occur as laterally-traceable sheets, dipping southwards, with conformable or slightly scoured basal contacts. These characteristics are typical of unconstrained subaerial sheet-flow associated with high-energy fluvial discharge (Ballance, 1984). The highly-rounded / spherical 'cannon-shot' morphology of many of the flint cobbles suggests that prior to subaerial deposition, their form has been modified by prolonged transport and mechanical abrasion within a high-energy turbulent system such as subglacial or

SAMPLE	n	CARB.	TRIASSIC				JURASSIC			CRETACEOUS					PAL-PL	TOTAL FLINT	IGN, META. & SED.		UNKN.
		chert	qtzite	vein qtz	schorl	TOTAL	*Rhax.* chert	sstn, lstn, irnstn & shell	TOTAL	sstn, lstn, irnstn & shell	Green. chert	Chalk	Flint	TOTAL	C-M Flint		N.Eng / Scot	Wales	
8-16 MM FRACTION																			
4/2c	628	0.0	0.8	2.3	0.2	3.3	0.7	0.0	0.7	0.0	0.2	0.0	87.0	87.2	7.6	96.3	0.9	0.0	0.2
9/3a	252	0.0	2.0	2.4	1.2	5.6	0.4	0.0	0.4	0.0	0.0	0.0	85.3	85.3	8.3	93.6	0.4	0.0	0.0
8/1a	347	0.0	3.8	3.2	0.0	7.0	0.0	0.3	0.3	0.3	0.0	0.0	79.0	79.3	12.4	82.1	1.9	0.0	0.3
7/g	689	0.1	2.2	2.6	0.0	4.8	0.0	0.0	0.0	0.0	0.6	0.0	83.0	83.6	11.0	84.6	0.5	0.0	0.1
5/2a	740	0.4	2.2	1.9	0.0	4.1	0.5	0.3	0.8	0.0	0.0	0.0	85.0	85.0	9.4	94.5	0.2	0.0	0.0
7/6	606	0.0	1.5	2.8	0.8	5.1	0.0	0.0	0.0	0.0	0.2	0.0	83.0	83.2	12.4	95.6	0.0	0.0	0.0
3/1a	536	0.0	3.1	4.7	0.4	8.2	0.2	0.6	0.8	0.0	0.6	0.0	81.5	82.1	7.5	89.0	0.6	0.0	0.0
16-32 MM FRACTION																			
4/2c	25	0.0	4.0	0.0	0.0	4.0	4.0	0.0	4.0	0.0	0.0	0.0	28.0	28.0	64.0	92.0	0.0	0.0	0.0
9/3a	50	0.0	4.0	0.0	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	60.0	60.0	36.0	96.0	0.0	0.0	0.0
8/1a	81	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	40.7	40.7	59.3	100.0	0.0	0.0	0.0
7/g	81	0.0	4.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	35.8	35.8	58.0	93.9	1.2	0.0	0.0
5/2a	66	0.0	0.0	1.5	1.5	3.0	0.0	0.0	0.0	0.0	0.0	0.0	76.9	76.9	19.7	97.0	0.0	0.0	0.0
7/6	86	0.0	2.3	0.0	0.0	2.3	0.0	0.0	0.0	0.0	0.0	0.0	32.6	32.6	43.0	96.7	0.0	0.0	0.0
3/1a	90	0.0	2.2	3.3	0.0	5.5	1.1	0.0	1.1	0.0	0.0	0.0	73.3	73.3	17.8	19.4	2.2	0.0	0.0

Table 3. Lithological composition of the 8-16 mm and 16-32 mm size fractions of gravel samples from Holt Quarry.

englacial drainage channel (Brennand, 1994; Gale and Hoare, 2007). The occurrence of erratic clast lithologies, the coarse grain size coupled with their roundness and sphericity, implies the close-proximity of the site to a glacier drainage portal (Gustavson and Boothroyd, 1987; Zielinski and van Loon, 2003). The development of sheet-like gravel bodies within proglacial environments (known as outwash plains or sandur) has been widely recognised within modern glacialenvironments and attributed to unconstrained sheet floods associated with flood events (Maizels, 1993) including glacier outburst floods (Maizels, 1997; Marren, 2005).

Overlying the gravel-dominated units, are thick stratified sand units that occur within the upper parts of Exposures A and B, and further up-profile within Exposure C. These stratified sands are dominated by planar and trough cross-bedded sand resting upon irregular and angular bounding surfaces. The geometry of these bounding surfaces appears to reflect erosion by scouring, minor channelisation, and lateral and forward migration of large subaqueous bedforms (dunes) often up the foresets of adjacent dunes. Directional measurements from bedding foresets indicate bedform migration towards the southwest, south and southeast. Units composed of horizontally-laminated sands record lower plane bed conditions associated with flow across bar surfaces. Lenses composed of clayey silt are suggestive of occasional and abrupt reductions in flow regime enabling suspension-settling under low energy conditions. Collectively, these facies point to sedimentation within a subaerial braided drainage (outwash) system characterised by bedform migration, channelisation and scouring within a shallow, probably broad channel (McDonald and Banerjee, 1971; Rust, 1972; Miall, 1977). Channelised drainage, in addition to unconstrained sheet-flow, is also a common characteristic of many modern outwash sandur (McDonald and Banerjee, 1971; Maizels, 1993; Marren, 2005) and is typically attributed to periods of background drainage from an adjacent glacier (Maizels, 1993; Marren, 2005).

Of particular importance is the presence of the normal and reverse faulting. Normal faulting (F3) and graben development probably relates to consolidation associated with loading or localised drying of the sediment pile. Reverse and thrust faulting, by contrast, occurred during at least four (F1, F2, F4 and F5) discrete episodes and indicates the sustained application of lateral shear (compressive) stresses to the sediments. Critically, truncation of particular faults by ongoing sedimentation indicates that deformation occurred contemporaneously with sediment deposition. These reverse and thrust faults are interpreted as providing evidence for lateral-pushing and

subsequent ice-contact deformation of the sediment by an adjacent glacier (Phillips *et al.*, 2002) with structural measurements indicating that stresses were consistently applied from the north.

Geological and Stratigraphic Context

As established within earlier sections, sands and gravels at Holt Quarry provide evidence for proglacial outwash sedimentation on a rapidly-aggrading outwash plane or sandur. Sedimentation was driven by phases of unconstrained sheet-flow attributed to elevated discharge events, punctuated by active channel incision and migration (i.e. anastomosing braided channels) under background lower-energy flow conditions (McDonald and Banerjee, 1971; Rust, 1972; Miall, 1977, 1978). Such hydrological characteristics are common within modern sandur areas such as Iceland where background outwash drainage is frequently interrupted by abrupt discharge events including glacier outburst floods (Maizels, 1993, 1997; Zielinski and van Loon, 2003; Marren, 2005).

The presence of reverse and low-angle thrust faulting suggest that unidirectional compressive stresses were being applied to the sediment pile from a northerly direction. This is important because it implies that deposits at Holt were being actively deformed by ice-marginal to proglacial glacitectonic processes during sedimentation – specifically, that the sequence at Holt was ice-contact. Similar styles of syn-depositional glacitectonic deformation have been recognised elsewhere along the Cromer Ridge including Stody (Pawley, 2006; Lee *et al.*, 2013); Briton's Lane Quarry (Banham, 1977) Roman Camp (Lee *et al.*, 2013), Trimingham cliffs (Lee *et al.*, 2013) and Gimingham Quarry near Trimingham (Lee *et al.*, 2013).

Sediments at Holt form part of a far more extensive proglacial outwash system that covers the southern flanks of the Cromer Ridge, extending and thinning southwards towards Norwich where it drapes and infills the immediate post-glacial topography (Straw, 1973; Straw and Clayton, 1979; Boulton *et al.*, 1984; Lunkka, 1994; Banham, 2000; Moorlock *et al.*, 2002; Hamblin *et al.*, 2005). Collectively outwash deposits in north Norfolk with this flint-dominated composition and geometric relationship to the underlying substrate form part of the Briton's Lane Formation (Lee *et al.*, 2004). Thicknesses of the Briton's Lane Formation vary markedly, with in places, thicknesses of 40 m attained (Pawley *et al.*, 2005). However, the modern distribution of the Britons

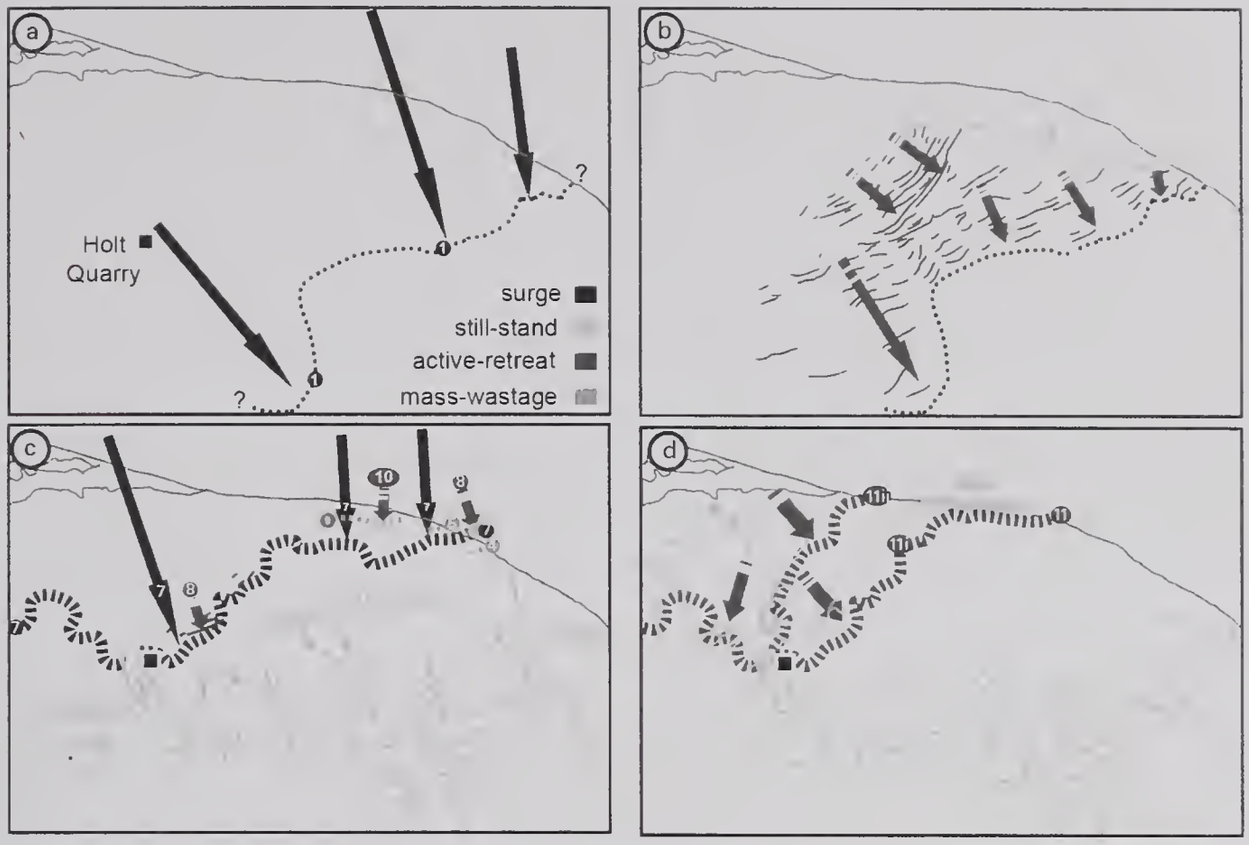

Fig. 7. Tentative model of ice-marginal retreat reconstructed from structural and geomorphological evidence (modified from Lee *et al.*, 2013).

Lane Formation is probably far-less extensive than it was originally, with considerable volumes of sediment subsequently removed by slope processes and fluvial erosion.

Nevertheless, the sequence at Holt contributes to the wider understanding of ice-marginal retreat in north Norfolk during the Anglian Glaciation (Fig. 7). Recently, Lee *et al.* (2013) presented a twelve-stage model for the last-known major Anglian ice advance (the A6 advance) into north Norfolk. Within this model, ice initially advanced much further south in north Norfolk than previous models suggest (Stage 1; Fig. 7a). A stepped 'active retreat' of the ice margin led to the development of several small lines of retreat moraines (Stage 2; Fig. 7b). This was followed by the establishment of a temporary still-stand along the line of the Cromer Ridge, and the construction of a prominent 'moraine complex' by repeated thrust-stacking during several minor 'superimposed' ice-marginal oscillations (Stages 3-8; Fig. 7b & c). The outwash sequence at Holt, was presumably generated when a considerable thickness of ice was abutting the ice-proximal (northern) side of the Cromer Ridge. This is because a suitably-thick mass of ice would be required to generate a sufficient hydraulic-gradient

for meltwater drainage to be driven to elevations of at least 55 m (assuming the Cromer Ridge was not originally ice-cored). Meltwater incision of the outwash sandur - generating the Briston Gap, enabled drainage to extend southwards and probably initiated the development of the post-Anglian Bure river valley. Subsequent thinning and withdrawal of ice from the Cromer Ridge, led to the stepped-development of several thrust-block morainic features as the ice margin retreated northwards (Stages 9-12; Fig. 7c & d). Identified remnants of these occur at Cromer (Banham, 1971), Weybourne Town Pit (Evans *et al.*, 2011) and several rounded ice-contact hillocks between Overstrand and Weybourne (West, 1957; Lee *et al.*, 2013).

CONCLUSIONS

- Aggregate extraction at Holt Quarry has exposed a complex sequence of sands and gravels deposited as part of a proglacial / ice-marginal braided outwash system during the later stages of the Anglian Glaciation.
- Glacitectonic structures preserved within the deposits reveals that deformation produced by glacier ice pushing into the sediment pile occurred during active outwash sedimentation.
- Outwash sediments at Holt form part of a more extensive glacial outwash system the remnants of which, extend southwards towards Norwich.

ACKNOWLEDGEMNTS

The author wishes to thank several individuals regarding their friendly and engaging discussions relating to the Cromer Ridge and the glacial geology of north Norfolk including Peter Allen, Stephen Booth, Helen Burke, David Evans, Richard Hamblin, Jane Hart, Brian Moorlock, Steve Pawley, Emrys Phillips, Adrian Read, Jim Riding, Jim Rose, David Vaughan-Hirsch and Martin Warren. Oliver Wakefield and Jenni Turner are warmly thanked for their comments on an earlier version of the manuscript. JRL publishes with the permission of the Executive Director of the British Geological Survey (NERC).

REFERENCES

BALLANCE, P.F. 1984. Sheet-flow-dominated gravel fans of the non-marine middle Cenozoic Simmler Formation, central California. *Sedimentary Geology*, **38**, 337-359.

BANHAM, P.H. 1966. The significane of till pebble lineations and their relation to folds in two Pleistocene tills at Mundesley, Norfolk. *Proceedings of the Geologists' Association*, **77**, 469-474.

BANHAM, P.H. 1968. A preliminary note on the Pleistocene stratigraphy of northeast Norfolk. *Proceedings of the Geologists' Association*, **79**, 507-512.

BANHAM, P.H. 1975. Glaciotectonic structures: a general discussion with particular reference to the Contorted Drift of Norfolk. In: Wright, A E, and Moseley, F (eds.). *Ice Ages: Ancient and Modern*, 69-94, Seel House Press, Liverpool.

BANHAM, P.H. 1977. Glaciotectonites in till stratigraphy. *Boreas*, **6**, 101-105.

BANHAM, P.H. 1977. Stop 3. Briton's Lane Gravel Pit. In: West, R.G. (ed.). *East Anglia. Guidebook for Excursions A1 and C1, INQUA X Congress 1977*, 28-29, Geo Abstracts, Norwich.

BANHAM, P.H. 1988. Polyphase glaciotectonic deformation in the Contorted Drift of Norfolk. In: Croot, D. (ed.). *Glaciotectonics: Forms and Processes*, 27-32, Balkema, Rotterdam.

BANHAM, P.H. 2000. C.E. Ranson's data from the glacifluvial and other sands and gravels of north Norfolk, England. *Bulletin of the Geological Society of Norfolk*, **50**, 5-20.

BANHAM, P.H., GIBBARD, P.L., LUNKKA, J.P., PARFITT, S. A., PREECE, R.C. & TURNER, C. 2001. A critical assessment of 'a new glacial stratigraphy for eastern England. *Quaternary Newsletter*, **93**, 5-14.

BANHAM, P.H. & RANSON, C.E. 1965. Structural study of the Contorted Drift and disturbed chalk at Weybourne, north Norfolk. *Geological Magazine*, **102**, 164-174.

BOULTON, G.S. COX, F., HART, J.K. & THORNTON, M. 1984. The glacial geology of Norfolk. *Bulletin of the Geological Society of Norfolk*, **34**, 103-122.

BOWEN, D.Q., ROSE, J., MCCABE, A.M. & SUTHERLAND, D.G. 1986. Correlation of Quaternary glaciations in England, Ireland, Scotland and Wales. *Quaternary Science Reviews*, **5**, 299-340.

BRENNAND, T.A. 1994. Macroforms, large bedforms and rhythmic sedimentary sequences in subglacial eskers, south-central Ontario: implications for esker genesis and meltwater regime. *Sedimentary Geology*, **91**, 9-55.

CLARK, C.D., GIBBARD, P.L. & ROSE, J. 2004. Pleistocene glacial limits in England, Scotland and Wales. In: Ehlers, J. and Gibbard, P.L. (eds.). *Glaciations of the World, Europe*, 47-82, Elsever, Amsterdam.

EHLERS, J, & GIBBARD, P L. 1991. Anglian glaciation and glacial deposits in Britain and the adjoining offshore regions. In: Ehlers, J., Gibbard, P.L. & Rose, J. (eds.). *Glacial deposits in Great Britain and Ireland*, 17-24, Balkema, Rotterdam.

EHLERS, J., GIBBARD, P.L. & WHITEMAN, C.A. 1987. Recent investigations of the Marly Drift of northwest Norfolk, England. In: van der Meer, J.J.M. (ed.). *Tills and glaciotectonics*, 39-54, Balkema, Rotterdam.

EHLERS, J., GIBBARD, P.L. & WHITEMAN, C.A. 1991. The glacial deposits of northwestern Norfolk. In: Ehlers, J., Gibbard, P.L. & Rose, J. (eds.). *Glacial deposits in Great Britain and Ireland*, 223-232, Balkema, Rotterdam.

EVANS, D.J.A., PHILLIPS, E.R., HIEMSTRA, J.F. & AUTON, C.A. 2006. Subglacial till: Formation, sedimentary characteristics and classification. *Earth-Science Reviews*, **78**, 115-176.

EVANS, H.M., LEE, J.R. & RIDING, J.B. 2011. A thrust-stacked origin for inter-stratified till sequences: an example from Weybourne Town Pit, north Norfolk, UK. *Bulletin of the Geological Society of Norfolk*, **61**, 23-49.

FISH, P.R. & WHITEMAN, C.A. 2001. Chalk micropaleontology and the provenancing of Middle Pleistocene Lowestoft Formation Till in eastern England. *Earth Surface Processes and Landforms*, **26**, 953-970.

FISH, P.R., WHITEMAN, C.A., MOORLOCK, B.S.P., HAMBLIN, R.J.O. & WILKINSON, I.P. 2000. The glacial geology of the Weybourne area, north Norfolk: a new approach. *Bulletin of the Geological Society of Norflok*, **50**, 21-45.

FLEMING, E.J., STEVENSON, C.T.E. & PETRONIS, M.S. 2013. New insights into the deformation of a Middle Pleistocene glaciotectonised sequence in Norfolk, England through magnetic and structural analysis. *Proceedings of the Geologists' Association*, **124**, 834-854.

GALE, S.J. & HOARE, P.G. 1991. *Quaternary sediments : petrographic methods for the study of unlithified rocks*. Wiley, Chichester.

GALE, S.J. & HOARE, P.G. 2007. The age and origin of the Blakeney esker of north Norfolk: implications of the glaciology of the southern North Sea Basin. In: Hambrey, M.J., Christoffersen, P., Glasser, N.F. & Hubbard, B.P. (eds.). *Glacial Sedimentary Processes and Products*, 203-234, International Association of Sedimentologists, Special Publication 39, Blackwell, Oxford.

GUSTAVSON, T.C. & BOOTHROYD, J.C. 1987. A depositional model for outwash, sediment sources, and hydrologic characteristics, Malaspina Glacier, Alaska: a modern analog of the southeastern margin of the Laurentide Ice Sheet. *Geological Society of America Bulletin*, **99**, 187-200.

HAMBLIN, R.J.O., MOORLOCK, B.S.P., ROSE, J., LEE, J.R., RIDING, J.B., BOOTH, S.J. & PAWLEY, S.M. 2005. Revised Pre-Devensian glacial stratigraphy in Norfolk, England, based on mapping and till provenance. *Geologie en Mijnbouw*, **84**, 77-85.

HART, J.K. 1990. Proglacial glaciotectonic deformation and the origin of the Cromer Ridge push moraine, north Norfolk, England. *Boreas*, **19**, 165-180.

HART, J.K. 2007. An investigation of subglacial shear zone processes from Weybourne, Norfolk, UK. *Quaternary Science Reviews*, **26**, 2354-2374.

HART, J.K & BOULTON, G.S. 1991. The glacial drifts of northeastern Norfolk. In: Ehlers, J., Gibbard, P.L. & Rose, J. (eds.). *Glacial deposits in Great Britain and Ireland*, 233-243, Balkema, Rotterdam.

LEE, J R. 2003. *Early and Middle Pleistocene lithostratigraphy and palaeoenvironments in north-eastern East Anglia, UK*. Unpublished PhD thesis, Royal Holloway, University of London.

LEE, J.R., BOOTH, S.J., HAMBLIN, R.J.O., JARROW, A.M., KESSLER, H., MOORLOCK, B.S.P., MORIGI, A.N., PALMER, A.P., RIDING, J.B. & ROSE, J. 2004. A new stratigraphy for the glacial deposits around Lowestoft, Great Yarmouth, North Walsham, and Cromer, East Anglia, UK. *Bulletin of the Geological Society of Norfolk*, **53**, 3-60.

LEE, J.R., BUSSCHERS, F.S. & SEJRUP, H.P. 2012. Pre-Weichselian Quaternary glaciations of the British Isles, The Netherlands, Norway and adjacent marine areas south of 68°N: implications for long-term ice sheet development in northern Europe. *Quaternary Science Reviews*, **44**, 213-228.

LEE, J.R., PAWLEY, S.M., ROSE, J., MOORLOCK, B.S.P., RIDING, J.B., HAMBLIN, R.J.O, CANDY, I., BARENDREGT, R.W., BOOTH, S.J. & HARRISON, A.M. 2008. Pre-Devensian lithostratigraphy of shallow marine, fluvial and glacial sediments in northern East Anglia – Field Guide. In: Candy, I., Lee, J.R. & Harrison, A.M. (*eds.*). The Quaternary of northern East Anglia, 42-59, *Quaternary Research Association*, London.

LEE, J R & PHILLIPS, E.R. 2008. Progressive soft sediment deformation within a subglacial shear zone-a hybrid mosaic-pervasive deformation model for Middle Pleistocene glaciotectonised sediments from eastern England. *Quaternary Science Reviews*, **27**, 1350-1362.

LEE, J.R. & PHILLIPS, E. 2013. Glacitectonics – a key approach to examining ice dynamics, substrate rheology and ice-bed coupling. *Proceedings of the Geologists' Association*, **124**, 731-737.

LEE, J.R., PHILLIPS, E., BOOTH, S.J., ROSE, J., JORDAN, H.M., PAWLEY, S.M., WARREN, M. & LAWLEY, R.S. 2013. A polyphase glacitectonic model for ice-marginal retreat and terminal moraine development: the Middle Pleistocene British Ice Sheet, northern Norfolk, UK. *Proceedings of the Geologists' Association*, **124**, 753-777.

LEE, J.R., PHILLIPS, E., EVANS, H.M. & VAUGHAN-HIRSCH, D. 2011b. An introduction to the glacial geology and history of glacitectonic research in northeast Norfolk. In: Lee, J.R., Phillips, E. & Evans, H.M. (eds.). *Glacitectonics - Field Guide*, 101-115, Quaternary Research Association, London.

LEE, J.R., ROSE, J., HAMBLIN, R.J., MOORLOCK, B.S.P., RIDING, J.B., PHILLIPS, E., BARENDREGT, R.W. & CANDY, I. 2011a. The Glacial History of the British Isles during the Early and Middle Pleistocene: Implications for the long-term development of the British Ice Sheet. In: Ehlers, J., Gibbard, P.L. & Hughes, P.D. (ed.). *Quaternary Glaciations–Extent and Chronology, A Closer look*, 59-74, Development in Quaternary Science 15, Elsevier, Amsterdam.

LUNKKA, J.P. 1994. Sedimentation and lithostratigraphy of the North Sea Drift and Lowestoft Till Formations in the coastal cliffs of northeast Norfolk. *Journal of Quaternary Science*, **9**, 209-233.

MAIZELS, J. 1993. Lithofacies variations within sandur deposits: the role of runoff regime, flow dynamics and sediment supply characteristics. *Sedimentary Geology*, **85**, 299-325.

MAIZELS, J. 1997. Jökulhlaup deposits in proglacial areas. *Quaternary Science Reviews*, **16**, 793-819.

MARREN, P.M. 2005. Magnitude and frequency in proglacial rivers: a geomorphological and sedimentological perspective. *Earth-Science Reviews*, **70**, 203-251.

MCDONALD, B.C. & BANERJEE, I. 1971. Sediments and bed forms on a braided outwash plain. *Canadian Journal of Earth Sciences*, **8**, 1282-1301.

MIALL, A.D. 1977. A review of the braided-river depositional environment. *Earth-Science Reviews*, **13**, 1-62.

MIALL, A.D. 1978. Lithofacies types and vertical profile models in braided river deposits: a summary. In: Miall, A.D. (ed.). *Fluvial Sedimentology*, 597-604, Canadian Society of Petroleum Geologists, Memoir 5.

MOORLOCK, B.S.P., BOOTH, S.J., FISH, P., HAMBLIN, R.J.O, KESSLER, H., RIDING, J.B, & ROSE, J. 2000. Briton's Lane Gravel Pit, Beeston Regis (TG 168415). In: Lewis, S.G., Whiteman, C.A. & Preece, R.C. (eds). *The Quaternary of Norfolk and Suffolk*, 115-118, Quaternary Research Association, London.

MOORLOCK, B.S.P., HAMBLIN, R.J.O, BOOTH, S.J. & KESSLER, H. 2002. Geology of the Cromer district - a brief description of the geological map. *Sheet Explanation of the British Geological Survey, 1:50 000 Sheet Cromer 131 (England and Wales)*, British Geological Survey, Nottingham.

PAWLEY, S.M. 2006. *Quaternary glaciations of north and west Norfolk.* Unpublished PhD Thesis. thesis, University of London.

PAWLEY, S.M., BAILEY, R.M., ROSE, J., MOORLOCK, B.S,P, HAMBLIN, R.J.O., BOOTH, S.J. & LEE, J.R. 2008. Age limits on Middle Pleistocene glacial sediments from OSL dating, north Norfolk, UK. *Quaternary Science Reviews*, **27**, 1363-1377.

PAWLEY, S.M., CANDY, I, & BOOTH, S.J. 2006. The Late Devensian terminal moraine ridge at Garrett Hill, Stiffkey valley, north Norfolk, England. *Proceedings of the Yorkshire Geological Society*, **56**, 31-39.

PAWLEY, S.M., LEE, J.R., RIDING, J.B., MOORLOCK, B.S.P., HAMBLIN, R.J.O., ROSE, J. & CROFTS, R.G. 2005. The stratigraphy of the Briton's Lane borehole and quarry, Beeston Regis, north-east Norfolk. *Bulletin of the Geological Society of Norfolk*, **55**, 15-42.

PERRIN, R.M.S., ROSE, J. & DAVIES, H. 1979. The distribution, variation and origins of pre-Devensian tills in eastern England. *Philosophical Transactions of the Royal Society of London*, **B287**, 535-570.

PHILLIPS, E, & LEE, J.R. 2013. Development of a subglacial drainage system and its effect on glacitectonism within the polydeformed Middle Pleistocene (Anglian) glacigenic sequence of north Norfolk, Eastern England. *Proceedings of the Geologists' Association*, **124**, 855-875.

PHILLIPS, E., LEE, J.R. & BURKE, H.F. 2008. Progressive proglacial to subglacial deformation and syntectonic sedimentation at the margins of the Mid-Pleistocene British Ice Sheet: evidence from north Norfolk, UK. *Quaternary Science Reviews*, **27**, 1848-1871.

PHILLIPS, E.R, EVANS, D.J.A & AUTON, C.A. 2002. Polyphase deformation at an oscillating ice margin following the Loch Lomond Readvance, central Scotland, UK. *Sedimentary Geology*, **149**, 157-182.

PREECE, R.C., PARFITT, S.A., COOPE, G.R., PENKMAN, K.E.H, PONEL, P. & WHITTAKER, J.E. 2009. Biostratigraphic and aminostratigraphic constraints on the age of the Middle Pleistocene glacial succession in north Norfolk, UK. *Journal of Quaternary Science*, **24**, 557-580.

REID, C. 1882. *The geology of the country around Cromer*. H.M.S.O Memoir of the Geological Survey, England and Wales, London.

ROSE, J. 2009. Early and Middle Pleistocene landscapes of eastern England. *Proceedings of the Geologists' Association*, **120**, 3-33.

RUST, B R. 1972. Structure and process in a braided river. *Sedimentology*, **18**, 221-245.

SCHEIB, A.J., LEE, J.R., BREWARD, N. & RIDING, J.B. 2011. Reconstructing flowpaths of the Middle Pleistocene British Ice Sheet in central-eastern England : the application of regional soil geochemical data. *Proceedings of the Geologists' Association*, **122**, 432-444.

SLATER, G. 1926. Glacial tectonics as reflected in disturbed drift deposits. *Proceedings of the Geologists' Association*, **37**, 392-400.

SOLOMON, J.D. 1932. On the heavy mineral assemblages of the Great Chalky Boulder-clay and Cannon-shot Gravels of East Anglia. *Geological Magazine*, **69**, 314-320.

STRAW, A. 1973. The glacial geomorphology of central and north Norfolk. *The East Midland Geographer*, **5**, 333-354.

STRAW, A. 1979. In: Straw, A. & Clayton, K.M. *The geomorphology of the British Isles*. Methuen, London.

STRAW, A, & CLAYTON, K. 1979. *The geomorphology of the British Isles*. Methuen, London.

WALLER, R.I., PHILLIPS, E., MURTON, J.B., LEE, J.R. & WHITEMAN, C.A. 2011. Sand intraclasts as evidence of subglacial deformation of Middle Pleistocene permafrost, North Norfolk, UK. *Quaternary Science Reviews*, **30**, 3481-3500.

WEST, R.G. 1957. Notes on a preliminary map of some features of the drift topography around Holt and Cromer, Norfolk. *Transactions of the Norfolk and Norwich Naturalists' Society*, **18**, 24-29.

WEST, R.G. & DONNER, J.J. 1956. The glaciations in East Anglia and the East Midlands: a differentiation based on stone-orientation measurements of the tills. *Quarterly Journal of the Geological Society of London*, **112**, 69-91.

ZIELINSKI, T. & VAN LOON, A.J. 2003. Pleistocene sandur deposits represent braidplains, not alluvial fans. *Boreas*, **32**, 590-611.

[Manuscript received 1 October 2014; revision accepted 16 October 2014]

GEOLOGICAL SOCIETY OF NORFOLK WEBSITE

The Geological Society of Norfolk (GSN) website can be found at:

http://www.norfolkgeology.co.uk

The contents and abstracts of the Bulletins, starting in 1953, are all available for download on the website. Many back issues are available in print form, see p. 40.

The society also has a Facebook page and an Earth Science Database containing over a thousand articles relevant to the geology of Norfolk.

WILLIAM SMITH'S GEOLOGICAL SECTIONS ACROSS EAST ANGLIA

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ABSTRACT

William Smith's hitherto unpublished geological sections across East Anglia (c. 1819) are discussed, with further comments on the sections published shortly thereafter by Smith's one-time trainee, the Norfolk-based surveyor Richard Cowling Taylor.

INTRODUCTION

The surveyor-engineer William Smith (1769-1839), 'the father of English geology', spent a good deal of time in East Anglia during the first ten years of the nineteenth century, a time when the region was very active both scientifically and politically (Ketton-Cremer, 1962; Markham, 2012; Banham, 2013 and refs therein). Some of Smith's geological work in the region was published and the William Smith archive at the Oxford University Museum of Natural History (OUMNH) also holds a number of Smith's original drawings of particular geological sites (Torrens, 2006, Plunkett, 2012, Banham 2012). Around 1819, despite bankruptcy and semi-retirement to Yorkshire during that year (Torrens, 2003), Smith managed to publish with John Cary geological maps of many English counties, including both Norfolk and Suffolk (see **Note 1**). In addition, the Smith archive contains hitherto unpublished drafts of two geological vertical sections across East Anglia (Fig. 1). Now that the Smith archive has been digitised, these sections can also be accessed online (see **Note 2**).

At the same time we can take note of sections published shortly thereafter by Smith's protege and fellow surveyor, Richard Cowling Taylor of Norfolk. These sections were recently reprinted to a high standard (Wood, 2000) and are not reproduced here.

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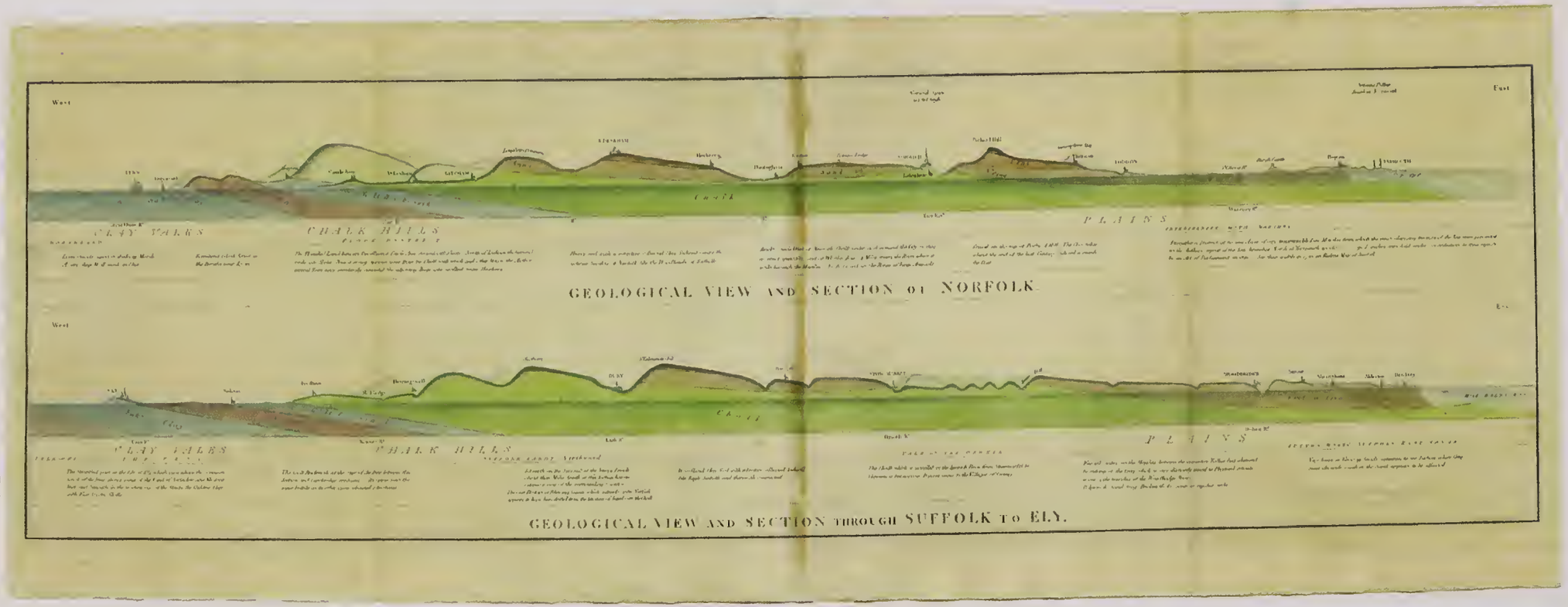

Fig. 1. Geological view and section of Norfolk [and] Suffolk to Ely, by William Smith ca. 1819. A high quality version of this image can be viewed online at www.oum.ox.ac.uk/collect/library4.htm Item:[WS/G/1/006]. This version is reproduced with permission of Oxford University Museum of Natural History.

SMITH'S SECTIONS

Topography

The Norfolk section is from Yarmouth to west of King's Lynn, ~100 km, and the Suffolk section is from Hollesley Bay to west of Ely, also ~100 km (Fig. 1; see also **Note 2** below) . No scale is given, but as the sections measure 1015 mm in length the horizontal scale is thus approximately 1: 100,000. That is, in the terms of those days, approximately 1.6 miles to 1", which is a larger scale than John Cary's 2.5 miles to 1" base maps used by Smith for his county geological maps. It is possible that Smith was informed by Hodskinson's map of Suffolk (1783) and Faden's map of Norfolk (1797; see Phillips, 1844, p. 52), both published at the larger scale of 1 mile to 1". Fully triangulated maps by the newly formed Ordnance Survey, also at a scale of 1 mile to 1", were still incomplete for East Anglia in 1810, and OS maps in general were not released until 1816, after the end of the war with France. Most significantly, all these maps indicate relief by shading only; the Ordnance Survey's co-ordinated, national programme of levelling height above sea level was not completed until 1840 (Owen & Pilbeam, 1992; Oliver, 2005). However, Smith had surveyed many areas for clients, particularly near the coast, and he knew the region well. Thus he was able to exaggerate the vertical scale (c. x30) whilst maintaining a broadly realistic profile. Also, Smith helpfully projected on to the plane of section geological evidence from either side.

Geology

Smith's stratigraphical sequence is numbered from the top down, in the manner of those times and as still preferred by archaeologists, miners and some borehole workers. In all, Smith recognised and coloured twelve main lithostratigraphical units within these cross sections:

1 - Alluvium, Gravel and Blown Sand.

- bones of large mammals found in these gravels at Costessy
- Breckland blown sand ' drifted from the stratum of sand over the Chalk'
- 'blowing sand' from the Crag below in East Suffolk

2 - Alluvial Clay

- soil developed on 'retentive alluvial clay' on Norfolk Heights and Suffolk 'Woodlands'

3-4 - Crag, Sand and Brickearth

- 'At Ipswich, Sand, Crag & Brickearth etc. occur in regular order' (from above to below, presumably)

5 - Chalk

6 - marked at base of Chalk in the West, but not named – Red Chalk?

7 - Golt Brickearth (i.e. Gault Clay)

Smith used fossils (unspecified) to confirm this

8-10 - Sand (i.e. Lower Greensand)

- 'same sands as at Swindon and Shotover Hill' (near Oxford)
- (8, 9, 10 - ? Carstone, Snettisham Clay & Sandringham Sand)

11 - Oaktree Clay (i.e. ~ Kimmeridge Clay)

- ' with Flat Oyster Shells'

12 - Sand (? Corallian)

Smith's pre-glacial succession (3-12) seems remarkably good for a first ever shot. However, the glacial succession (1 (part)-2) clearly puzzled him. This is not surprising, because the glacial concept did not begin to influence thinking in Britain until the middle of the nineteenth century. Moreover, Smith's earlier work had been mainly in the West Country where superficial deposits are much less prominent. At the surface in central Norfolk and Suffolk, where the Lowestoft Till is dominant, Smith recorded 'retentive alluvial clay' (2), perhaps giving some credence to the

contemporary understanding that most superficial deposits had resulted from 'The Deluge', otherwise known as 'Noah's Flood'. However, as Plunkett (2012) has noted, in East Anglia Smith does not call it 'Diluvium', the term he and others used elsewhere for superficial deposits then thought to have resulted from 'The Deluge'.

TAYLOR'S SECTIONS

During the decade that followed, Richard Cowling Taylor (1789-1851) published four geological sections across the region, recently published in full colour by Wood (2000, plates 1, 2; see also plates 3 & 5). In 1810, Suffolk-born and Norfolk-based Taylor carried out trainee surveyor 'work experience' in South Wales under William Smith. Thereafter Taylor became a keen geologist and they exchanged observations until 1818 (Banham, 2012 and references therein). By contrast, Taylor's sections are broadly from south to north, and are amplified by his large-scale drawings of important sites. Taking these all together, some advances in stratigraphy are clear. None of Taylor's sections cross the outcrop of the Gault Clay in the west, but for the Hunstanton cliffs a large-scale section provides a remarkably detailed sequence of 'Greensand Carstone' overlain by Red Chalk and in turn by a finely sub-divided 'Lower Chalk without Flints'. Lower in the sequence farther west Taylor identifies only 'Blue Marle', rather than Smith's by then well established Oaktree Clay (~Kimmeridge Clay). However, Taylor recognises the main outcrop of the 'London Clay' in Essex, together with its largely unexposed northern extension to Norfolk, including 'Plastic Clay' (?Ormesby Clay) and 'Sand' (?Thanet Sand). Likewise, the Cromer Forest Bed is foreshadowed in 'Forest Wood' to the north of his 'Crag' unit. Above this, in North Norfolk, Taylor boldly describes the main part of the glacial sequence as 'Diluvium', even although it contains large 'Chalk Patches' (i.e. glacially thrust rafts). Smith's hesitation to use that term was justified. Again unlike Smith, Taylor sweeps into a single unit all near-surface sands and gravels.

CONCLUDING REMARKS

Smith and Taylor worked independently in East Anglia, but exchanged information about the region. Smith's publications did not include his long sections across the region, so Taylor's published sections were the first to reflect their joint

understanding. In the event, Taylor published no more on East Anglia because from 1830 onward he lived and worked in the USA. His sections would nevertheless have influenced the later sections across the region by S. Woodward (1833), and F.W Harmer (1877; based on surveys with S. V. Wood jun., 1865-70), both also helpfully re-published and discussed by Wood (2000).

ACKNOWLEDGEMENTS

Publication of the hitherto unpublished geological sections by William Smith is by kind permission of the Oxford University Museum of Natural History (OUMNH). Particular thanks are due to Kathleen Santry for providing advance electronic copies of the sections.

Note 1 – In addition to reprints of Smith's 'Great Map' of 1815, all twenty-one of William Smith's County Maps, including those of Norfolk and Suffolk, can now be purchased as reprints from the Geological Society of London at www.geolsoc.org.uk/smithcountymaps .

Note 2 – The William Smith archive has been digitised by the OUMNH in preparation for the celebration of the bicentenary of the publication in 1815 of Smith's 'Great Map'. The East Anglia sections dealt with here (Box 14, item 6 in the archive) can now be accessed online at www.oum.ox.ac.uk/collect/library4.htm as Item: [WS/G/1/006] "Geological view and section of Norfolk [and] Geological view and section through Suffolk to Ely."

REFERENCES

(List includes Torrens, H. S. 2003 & 2006 omitted from Banham, P.H. 2013)

BANHAM, P. H. 2012. Suffolk's first earth scientists; Arthur Young (1741-1820) and Richard Cowling Taylor (1789-1851) In: Dixon, R. (ed.) *A Celebration of Suffolk Geology: GeoSuffolk 10th Anniversary Volume*, 435-444, GeoSuffolk, Ipswich.

BANHAM, P. H. 2013. William Smith in Norfolk and Suffolk 1800-1818. *Bulletin of the Geological Society of Norfolk,* **63**, 43-53.

KETTON-CREMER, R.W. 1962. Felbrigg – The Story of a House. The Boydell Press, 365 pp.

OWEN, T. & PILBEAM, E. 1992. *Ordnance Survey; Map Makers to Britain since 1791*. Ordnance Survey, Southampton, 196 pp.

OLIVER, R. 2005. *Ordnance Survey Maps: A Concise Guide for Historians*. Charles Close Society, 256pp.

MARKHAM, R. 2012. A short history of geology at Ipswich Museum. In: Dixon, R. (ed.) *A Celebration of Suffolk Geology: GeoSuffolk 10th Anniversary Volume*, 429-434, GeoSuffolk, Ipswich.

PHILLIPS, J. 1844. *Memoirs of William Smith, LL.D.* (as reprinted in Torrens, H.S. 2003).

PLUNKETT, S. 2012. Prehistoric attitudes: a Suffolk pedigree. In: Dixon, R. (ed.) *A Celebration of Suffolk Geology: GeoSuffolk 10th Anniversary Volume*, 83-100, GeoSuffolk, Ipswich.

TORRENS, H. S. 2003. *Memoirs of William Smith, LL.D.* Bath Royal Literary and Scientific Institution, 288 pp.

TORRENS, H. S. 2006. Lost and found! The 'lost work' of William Smith (1769-1839) – the so-called 'father of English Geology'. *Geoscientist*, **16**, 22-23

WOOD, C. J. 2000. Hand-coloured geological cross-sections of Norfolk and illustrations of the Norfolk cliffs in the early literature – a geological pot-pourri. In: Dixon, R. (ed.) *The Geological Society of Norfolk 50th Anniversary Volume*, 15-22 & 7 plates.

[Manuscript received 10 February 2014; revision accepted 21 August 2014]

BACK ISSUES OF THE BULLETIN OF THE GEOLOGICAL SOCIETY OF NORFOLK AND 50th JUBILEE VOLUME

The Geological Society of Norfolk (GSN) has back issues of the Bulletin available for purchase as outlined below. The Bulletin may not be easily available at some institutions - except through Inter-Library Loan – so individuals might consider a recommendation for purchase by institution libraries.

At present we can supply all issues except volumes 19, 32 and 42. Volumes 23, 27 and 28 are in short supply (less than 10 remaining). Volumes 1-10 and 11-18 are only available as reprint volumes 38A and 39A.

There are plenty of copies of the now famous 'East Anglian Geology' issue, volume 34.

Back issues of the Bulletin are available at £3-50 per issue to GSN members and £10-00 per issue to non-members. For purchase of two or more issues it is cheaper for non-members to join the society (£10-00 per year) and buy at member price.

In addition, the society published a special Jubilee volume (edited by Roger Dixon) to commemorate its 50th anniversary. This volume is dedicated to Prof. Brian Funnell and contains a number of articles about Prof. Funnell, his research and the early days of the Society. The Jubilee Volume is free to GSN members. The remainder are available at cost (£8-50).

If you would like to place an order please discuss your requirements with Julian Andrews at UEA, preferably on the following e-mail address: j.andrews@uea.ac.uk

Or by post to: Prof. Julian Andrews, School of Environmental Sciences, University of East Anglia, Norwich, NR4 7TJ.

BOOK REVIEW

FREDERIC W. HARMER: A SCIENTIFIC BIOGRAPHY

John A. Kington, Springer Briefs in Environment, Security, Development and Peace, Vol. 19. Heidelberg 2014. 97p. 53 illus. £35.99 eBook, £44.99 Softcover

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F. W. Harmer (1835 – 1923) was a highly successful clothing manufacturer and an alderman and mayor of Norwich who, as an amateur, made significant contributions to the earth sciences. This book is an extension of an article about these contributions that appeared in a recent bulletin (Kington, 2013).

Harmer's geological interests went beyond his native Norfolk to cover most of Eastern England. However, his generally less well known contributions to palaeometeorology were on an even larger map and form one of the most interesting parts of this book (Chapter 4 p. 63-82). This is not too surprising, given that its author is himself a noted climatologist. Kington reveals that as early as 1901, Harmer published north pole-centred synoptic views of Pleistocene weather patterns for the entire northern hemisphere. In these he postulated patterns of atmospheric pressure for winter and summer seasons during both glacial and interglacial stages. Kington figures these alongside those published much later by Hubert Lamb. The limited scope of the ice sheets depicted in Harmer's glacial stage weather diagrams is intriguing, revealing the then general belief that the American and European ice sheets were not synchronous, but alternated through time. Kington gives some details of how dating evidence put paid to that curious notion.

The value of this section is increased by noting the importance to climate of the size and shape of oceans and continents, a theme Kington traces back to Lyell's 'Principles' of 1858. In pre-plate tectonic days such macro-geographical changes were often seen as caused by the rise and fall of sea-level and by the consequent drowning

Bull. geol. Soc. Norfolk (2014), **64**, 41-43.

and emergence of hypothetical land bridges. An extraordinary example of these, running entirely across the Atlantic from Norway to Greenland by way of Iceland, was invoked by Harmer to influence the degree of interconnection between the Atlantic and Arctic Oceans. Whatever the controlling factors, this is still very much a lively issue (e.g. Bujak and Bujak, 2014).

Kington's appropriately longer assessment of Harmer's larger contribution to geology (Chapter 3, p. 15- 61) is nevertheless somewhat less rewarding because it mainly stops at 1948. Harmer's broadly northward younging and cooling stratigraphy of the Crags was fossil-based, with molluscs as the most important component. As Peter Norton remarks in the Foreword, 'The days of a malacologically based stratigraphy are now past, despite my attempts to arrange one...' Research has moved on, and many disciplines now contribute to a new understanding of the Crags, based on evidence from boreholes as well as from the surface exposures then available to Harmer. There are many atmospheric sepia photographs (from the BGS archive, no less) of East Anglian cliffs and beaches, especially those showing the distinguished party members of the international excursion Harmer led in 1907. There is a good account of the history of work on the glacial sequence up to and including that by Harmer, and, in a rare flash to the present day, in the light of Harmer's thoughts on fluvial patterns reference is made to current discussions concerning the Bytham River.

Disappointed by a lack of reference to Harmer in some recent geology books, and impressed by Harmer's work in his own field of climatology, Kington sets out to maintain his hero's geological image. However, he makes no direct reference to any of the fulsome obituaries of ninety years ago (e.g. Boswell, 1924). Also, he does not help his case by largely ignoring references to Harmer's work in recent papers such as those conveniently gathered by Roger Dixon (2000, 2012) in two milestone anniversary volumes on East Anglian geology. Nevertheless, we can readily agree that Harmer's Monograph of the Crag Mollusca (with S.V. Wood, jun.) will remain a classic and that his early maps of the geology and of the distribution of glacial erratics still have an important influence on the development of geology in Eastern England.

Although this is a 'scientific biography', in a short section (Chapter 1, p. 1-3) there is mention of Harmer's significant contribution to industry in Norwich. In effect he single-handedly compensated for the passing of the cottage woollen industry by taking from Yorkshire both manufacturing technology and high quality fabric to create

a major clothing manufacturing business in Norwich. Michael Harmer's article about all this on the Harmer Family Association website could have been cited in this context. Photographs of Harmer as an alderman and mayor of the City are prominent in the book, however, as is an account of his impressive property in Cringleford near Norwich, where Kington himself also lives. Finally, on the boundary of the personal and the scientific, some space is given to correspondence in 1872 between Harmer and Charles Darwin. This concerned an anti-evolutionist who, to the annoyance of both, had written under the pseudonym 'Homo', but whose real name had been revealed as Lyon. Kington notes that this was the maiden name of Harmer's wife Maria, so it was no doubt a sensitive topic.

Overall, this interesting short book achieves its aim of confirming Harmer the amateur as a very influential East Anglian earth scientist and reveals him as a farsighted 'palaeometeorologist' of the Pleistocene period in general.

On technical matters, the relatively few references are split into short chapter end sections; this is no doubt the house style, but it will annoy some. In compensation, there is a very useful full bibliography of Harmer's works, including all of his draft notes and reports as carefully archived by the BGS, together with a helpful glossary of the wide range of scientific terms used throughout the text.

REFERENCES

BOSWELL, P. G. H., 1924. Frederic William Harmer (1835-1923). *Quarterly Journal of the Geological Society of London,* **80** pp. li-liii

BUJAK, J. & BUJAK, A, 2014. The Arctic Azolla Event. *Geoscientist*, **24**, 10-15.

DIXON, R. 2000 (ed.) *Geological Society of Norfolk 50th Anniversary Jubilee Volume*. Norwich. 99pp

DIXON, R. 2012 (ed.) *A Celebration of Suffolk Geology. GeoSuffolk 10th Anniversary Volume*. GeoSuffolk, Ipswich. viii & 475 pp.

KINGTON, J.A. 2013. Frederic William Harmer: geologist and pioneer palaeometeorologist. *Bulletin of the Geological Society of Norfolk*, **63,** 13-42.

[Manuscript received 15 October 2014; revision accepted 13 November 2014]

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Copies of the Bulletin (including older back copies) can be obtained from the editor at the address on p.1; it is issued free to members.

The illustration on the front cover is figure 7 from the article by Lee in this issue of the Bulletin. It shows a tentative model of Anglian ice marginal retreat in north Norfolk based on structural and geomorphological evidence.

ISSN0143-9286